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# Design of a Wearable Sensor System for Prevention of Fatigue-Induced Injuries in Baseball Pitching

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# WPI

## Design of a Wearable Sensor System for Prevention of Fatigue-Induced Injuries in Baseball Pitching

A Major Qualifying Project  
Submitted to the Faculty of the  
WORCESTER POLYTECHNIC INSTITUTE  
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Submitted by:  
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# Abstract

Ulnar collateral ligament (UCL) injuries are increasingly common in baseball pitchers of all levels and often are career ending. The aim of this project was to develop a wearable sensor system to quantify risk of UCL injury in baseball pitchers through correlation with fatigue indicated by deviations in forces and torques in the throwing arm during pitching. The outcome of this project was a wearable sensor and data analysis system which could be applicable to predicting risk of injury.

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Professor Troy and Dr. Magit for their expertise and guidance throughout the project.

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# Authorship

All components of this Major Qualifying Project were contributed to equally by all three team members.

All sections of this report were written, edited, and formatted equally by all three team members.

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# Chapter 1: Introduction

Ulnar collateral ligament (UCL) injuries are common in baseball pitchers, and are present at all levels from youth to collegiate. The number of UCL injuries in youth and high school baseball pitchers that required surgery increased from 0% in 1994, to 31% in 2010 [1]. In an analysis of baseball UCL reconstructive surgery patients, it was found that 89% of these patients were pitchers [2]. Baseball pitchers at the collegiate level have an increased risk of elbow injury due to their prolonged exposure and overworking of joint stresses [2]. Overall, it is reported that 15% of collegiate baseball pitchers feel pain and tenderness in their elbow resulting in limited movement, which is the result of the mechanics learned in youth pitching training [3].

Improper pitching mechanics have been cited as the major cause of elbow injuries in baseball pitchers [4]. Two different points of the pitch have been highlighted as areas of potential risk if not completed correctly: shortly before the shoulder is fully rotated out during the late cocking stage of the pitch, and shortly after the ball is released at the follow through [5]. At both of these points, the timing of movement and elbow position to the body are both extremely important [6]. In many cases, proper pitching mechanics decrease as pitching counts increase, posing a threat to the UCL and increasing the potential risk of UCL injury [7].

The UCL is one of the main stabilizers of the elbow joint. A damaged UCL results in decreased strength in flexion and extension of the elbow [8]. During the baseball pitch, the UCL is especially crucial as it produces a varus torque to counteract the dangerous valgus torque generated at the elbow. This varus torque has been measured to reach up to 34.6 Newton-meters in adult Major League pitchers. However, cadaveric testing of UCL's has shown the stress limits of the ligament to produce torques up to only 32.1 Newton-meters [5]. When the UCL is routinely expected to perform at, or just above, maximum capacity, it is crucial that pitching mechanics are executed correctly to decrease the risk of injury.

It is known that stresses and torques at the elbow joint are the causes of UCL tears, therefore, some of the primary methods of tracking throwing biomechanics take advantage of wearable sensors such as inertial measurement units (IMUs) or systems of motion capture. An IMU typically is composed of at least an accelerometer and a gyroscope to track acceleration and angular velocity of the arm -- the two metrics essential for deriving forces and torques. It has been shown that two of these sensors, one on the forearm and one on the upper arm, are able to

track the metrics of the forearm during the movements of baseball [9]. A single sensor device on the arm has been used previously, but in order for metrics to be tracked in this type of system, the angle of the arm in respect to the ground is used to derive all of the data [10].

Currently, there are a myriad of solutions available on the market to help players to improve their pitching mechanics. These available solutions are broken down into three different general categories: stretching and strengthening protocols, mobile applications and software's, and wearable braces. The most common stretching and strengthening protocol is the Yokohama Baseball-9, which prescribes a regimen of exercises to improve posture and range of motion in the elbow. Studied players who follow this regimen report 50% fewer elbow injuries than contemporaries who do not follow this regimen [11].

Hudl Technique is a mobile application that uses video recording and playback to compare a pitch of the user side by side to a video of a professional baseball pitcher, to allow the user to learn this motion and self-adjust based on the comparison. Many other applications on the market rely on the user to interpret the feedback and make adjustments accordingly [12]. A danger of this is that the biomechanics of the user vary enough from the professional pitcher, that making adjustments to more similarly reflect the professional pitcher could place the user at an increased injury risk.

The Bauerfeind Sports Elbow Brace is worn while pitching to mechanically limit the extension of the arm during the follow through phase of the pitch which limits the magnitude of the torque placed on the elbow, but this device is primarily aimed at post-operative rehabilitation rather than preventive means [13]. The Motus mThrow is a wearable sensor device that records pitching data to be downloaded onto a mobile app for interpretation. The sensor in the device is comprised of accelerometers and gyroscopes to monitor arm movement, calculating stress and torque at the UCL [14].

Although there are many available solutions on the market available to pitchers and their coaches, there are three primary gaps in these solutions. Firstly, most of the devices available for pitching mechanics improvement and injury prevention do not provide real time feedback. The use of mobile applications for video analysis can be useful for players practicing pitching form, but these applications require review of the pitching motion after the fact, and do not give feedback in terms of injury prevention [12]. The mThrow from Motus comes closer to giving real time feedback, but the data the mThrow collects must be downloaded onto a paired mobile

application after the fact. Meaning, that a pitcher could be throwing with potentially injurious mechanics and not know until after the practice or game is over [14].

Secondly, the strategies currently on the market for improving pitching mechanics do not give comprehensive feedback for injury prevention, as they do not provide defined solutions. The feedback provided by the current market approaches are subject to different interpretations among users, and commonly requires an expert opinion in deciphering the meaning of the outputs as it relates to injury prevention. Use of stretching and strengthening protocols has been shown to reduce elbow injuries, but because these solutions focus on generally preparing the arm for throwing, there is very limited feedback or monitoring of dangerous levels of torque at the elbow, making it difficult to assess the efficacy of the prevention [11]. Video analysis software provides feedback only after the pitch has been thrown and reviewed, leading to a delay in the analysis for risk of injury. Most of the time, the feedback from video analysis are visual cues when form deviates from what is considered standard, but this interpretation is left up to the user. These solutions do not interpret the data for the player, meaning that a high level of training paired with a considerable amount of time is needed for using this technology correctly [12]. The mThrow by Motus reports data including force and torque values at the elbow to report stress on the UCL during the pitch. These metrics are certainly important in terms of understanding injury mechanisms and prevention, but a majority of the feedback from the mThrow is raw data or it is presented in an abstract manner specialized only to the system [14]. Most players do not understand the healthy ranges of raw data for these metrics, meaning that a higher level of expertise is needed to take full advantage of the abilities of the mThrow device. Overall, the feedback given from these devices is left up to the interpretation of the user, making it variable and potentially incorrect for that individual pitcher.

Lastly, while every pitcher has their own variation of proper pitching mechanics, most current market devices do not account for this. The use of motion limiting braces does give some level of biomechanical feedback during the pitch, but in hindering the natural motion of a pitching form, these braces do not allow for customization of the movement [13]. Video analysis software will often put a pitch side by side with another pitcher to use as a standard [12]. However, an individual's deviation from this standard form provided by the software does not necessarily imply dangerous or incorrect mechanics on the part of the individual. The mThrow by Motus shows the stress on the UCL during a pitch on a stoplight system style scale, but the



pitching data and healthy ranges the mThrow uses are generalized, as the device does not require calibration for each individual that uses the device [14].

Based on the gaps identified in our background research in current market solutions, we aimed to design a wearable sensor system that calculates and sets a healthy baseline for the maximum forces and torques on the elbow and shoulder during a baseball pitch of an individual, detects significant deviation from the healthy baseline mechanics of an individual player, and reports this feedback out in an intuitive fashion that a player or coach could use for injury prevention. The sensor system uses accelerometers and gyroscopes to estimate angular velocity, and angular acceleration to derive the torques and forces experienced at the elbow and shoulder. This project focused on biomechanics data from both current devices on the market and current research documented in literature. The sensor system was validated through simultaneous arm mechanics and metric collection through Polhemus electromagnetic motion tracking technology. All subject collected data from the system was analyzed with a custom MATLAB script to derive acceleration, angular velocity, and torque of the elbow and shoulder.

To create this system, preliminary background information regarding elbow anatomy, baseball pitching mechanics, baseball pitching injury mechanisms, and motion sensor systems was researched. Through the assistance of Professor Karen Troy and Dr. David Magit, overarching requirements for the system were outlined, resulting in functional and non-functional requirements for the design. An overall design concept was generated after consideration of alternative designs with varying sensor components. A prototype of this sensor system design was created to conduct experimental tests in comparison with the Polhemus electromagnetic tracking system, while evaluating if all design requirements were met. Throughout this testing, iterative improvements to the prototype were made. Limitations of the final design were evaluated and future recommendations for increasing the value and effectiveness of the system were identified.

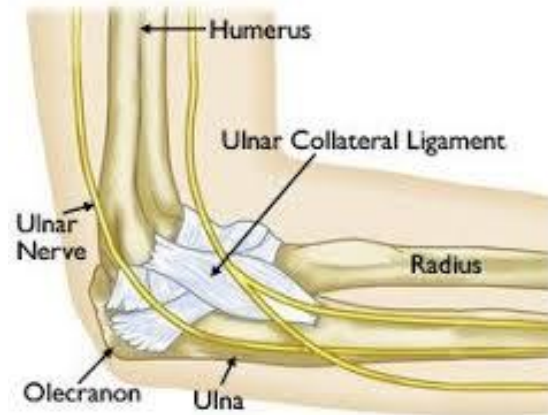
## Chapter 2: Literature Review

The purpose of this literature review is to provide general information and background on elbow anatomy and mechanics to illuminate the topic of elbow injuries, specifically UCL injuries in baseball pitching. This chapter details the anatomy and mechanics involved during the baseball pitch, including injury mechanisms. Topics include: basic elbow anatomy, mechanics of baseball pitching, pitching injury statistics, and pitching injury mechanisms. This chapter also covers the current state of research concerning baseball pitching injury mechanisms and prevention, and current market solutions and motion tracking systems used for pitching injury prevention.

### 2.1: Basic Elbow Mechanics and Anatomy

There are three joints that make up the elbow. The ulnohumeral joint is a hinge joint, capable of flexion and extension between the humerus and ulna bones; rotation is facilitated by the pivotal proximal radioulnar and radiohumeral joints. This allows the elbow to experience extension and flexion, as well as pronation and supination, and adduction and abduction. The elbow is typically a non-weight bearing joint, but due to muscle movements forces are experienced across the elbow joint [15]. In the elbow there is an anatomical group classified as passive stabilizers, including bony articular geometry and soft tissue stabilizers [16]. The ulnar collateral ligament (UCL), also known as the medial collateral ligament (MCL), and lateral collateral ligament (LCL) are two of the main stabilizing ligament complexes, shown in Figure 1 below. The UCL is composed primarily of the anterior bundle, as well as the posterior bundle and the transverse segment (which contributes minimally to joint stability). The LCL similarly is composed of multiple components: the radial collateral ligament, annular ligament, lateral ulnar collateral ligament and accessory lateral collateral ligament. In contrast to the UCL, the tension on the LCL is not significantly affected by extension and flexion, as it is close to the axis of rotation. Neither of the two main components of the UCL originate on the axis of rotation, and as such the two components do not experience uniform tension during elbow flexion and extension. The removal or destruction of the UCL decreases joint stability in the elbow at varying points of flexion and extension. The radial collateral ligament of the elbow provides strength between the humerus and annular ligament of the radius and is attached by the lateral epicondyle, which also

aids in elbow supination and extensor muscles attachment [8]. The medial epicondyle works in the same way as the lateral epicondyle, but is larger, is located more posteriorly on the humerus, and also aids in the attachment of flexor muscles and the UCL [8].



*Figure 1. Anatomical diagram of the elbow showing UCL location [17].*

The primary limiting factor in extension is the anterior bundle of the UCL, likewise, the most limiting factor in flexion is the posterior fibers [18]. Generally, the fibers which experience the greatest percent of elongation generate the greatest counteracting force. In addition to the tension force from the ligaments, there is a counteractive compressive force from the articular cartilage; the balance of these forces is what limits the motion of the joint. The fact that the elbow is not truly a hinge joint results in the tension of component fibers continually changing, such that not all fibers are equally taut at all times. In addition to the deviation from ideal circular anatomy, the articular cartilage deforms under stress and there is a screw axis. The way in which loads transfer to the elbow differently depending on the position of the elbow [19]. When in full extension, to 30 degrees of flexion, and the forearm in pronation, the highest loads were observed at the radiohumeral joint during range of motion exercises. The anterior complex of the UCL is the strongest and stiffest ligament, and the weakest is the posterior UCL. During arm movements, the muscles in the forearm, as well as upper arm, are most engaged during flexion movements and decrease with increasing flexion angle of the elbow [15]. The maximum forces experienced in the elbow joints typically range from 350-2094N [15].

In full flexion the forearm will typically reach 150 degrees from the stretched arm [20]. Extension can be either at the zero degree, or 10 degrees below the anatomical neutral position. In flexion the average torque created at the elbow for males and females is 7 kg-m and 3.5 kg-m

respectively; in extension it is 4 kg-m and 2 kg-m. The elbow can rotate 80-90 degrees in both supination and pronation from anatomical normal (which in this case is defined as 90-degree flexion). The torque from supination and pronation is 800-900 g-m and 350-550 g-m in males and females respectively [20].

## 2.2: Mechanics of Baseball Pitching

The movements and mechanics of the overhead baseball pitch are quite complex. The internal forces and torques that occur in the body during the various phases of the pitch are complicated and can be highly taxing on the involved tissues. The neuromuscular memory of the baseball pitch is typically developed at a young age, where proper technique retention of pitching mechanics is vital [21]. The term “pitching mechanics” was defined by Calabrese as the coordinated sequence of movements and muscular forces that come together to propel a baseball forward, with both high velocity and target accuracy. To better understand these mechanics, the overhead baseball pitch has been divided into five distinct phases: the wind-up, the stride or early cocking, late cocking, the acceleration, and the deceleration or follow through [6]. In all of these phases, forces are developing from different parts of the body and there are various directions of both forces and torques occurring. Shoulder and elbow kinematics are most often reported as the summation of the internal forces and torques applied to the entire arm and the forearm, respectively. The forces on the shoulder joint and the elbow joint are caused by the musculature, osseous, and tissue ligaments surrounding each joint [5].

### 2.2.1: The Kinetic Chain

The kinetic chain occurs during the baseball pitch, where forces generated in the lower extremities of the body are transferred to the more distal regions of the body to propel the baseball forward [6]. A key concept in the kinetic chain is the summation of speed principle, which states that the optimal energy transfer between two parts of the kinetic chain occurs when the subsequent segment begins to rotate as the prior segment has reached the maximum angular velocity [22]. In relation to pitching performance, this indicates that the timing of each phase of the pitch is crucial for optimal velocity and accuracy. The summation of speed principle also gives insight into pitching injury mechanisms; if the rotational timing between segments of the kinetic chain is off, then the transfer of momentum through the body will be ineffective [23].

A kinematic contribution analysis is used to study the contributions to the kinetic chain from each segment of the body in all three dimensions [24]. In analyses of baseball pitching, a resultant velocity vector at the hand, the most distal region of the kinetic chain, is partitioned into velocity vectors representing the contributions from each prior segment of the body. A kinematic contribution analysis is helpful for understanding the effectiveness of each part of the body in increasing the maximum velocity at the hand during a pitch, but it will not provide any finite force or torque values for each segment [23].

Induced acceleration analysis (IAA) has been used to investigate segmental contributions to the kinetic chain in baseball pitching kinematics. IAA is useful because it can analyze torque components during the rotation of a joint [23]. IAA has been used to specifically investigate the effects of the trunk segment of the kinetic chain on shoulder and elbow torques, showing that the counterclockwise rotation of the trunk, paired with the horizontal adduction of the shoulder plays a key role in producing rapid elbow extension, and high elbow torques [25]. A study investigating joint angular velocities during the baseball pitch also found that increased angular velocities of the trunk and upper arm resulted in acceleration at the elbow and hand, supporting the theory that motion at the trunk impacts the elbow joint [26].

### 2.2.2: Phases of the Pitch

The six phases of the baseball pitch can be seen in Figure 2 below.

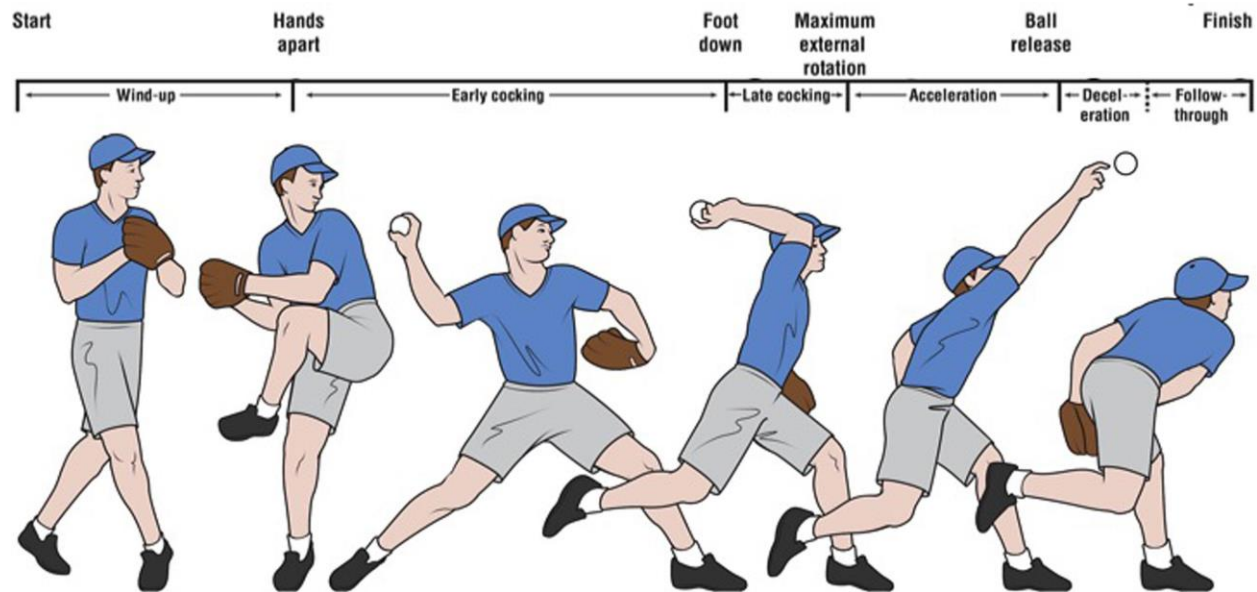


Figure 2. The five main phases of the baseball pitch (Reprinted from *Operative Techniques in Sports Medicine*, Volume 24, Erickson, Brandon J., Thorsness, Robert J., Hamamoto, Jasont T., Verma, Nikhil N., *The Biomechanics of Throwing*, Pages 156-161, Copyright (2016), with permission from Elsevier) [27].

The wind-up phase, the first phase of the baseball pitch, begins when the pitcher moves from a static position with both feet on the mound, facing home plate (the target). Next, the pitcher turns away from the target, keeping the foot of the pitching arm side planted. This leg is referred to as the stance leg, while the leg that is lifted is referred to as the lead leg. The phase is completed when the opposite knee is brought up to maximum height, and the baseball glove is brought across the body to meet the pitching hand, which is slightly cocked. This final position of the wind-up is called the balance point. The wind-up takes about 0.5-1.3 seconds to complete [6]. During this phase, the risk of injury is low relative to the other pitching phases due to the fact that the muscle activity at the rotator cuff, scapular stabilizers, and deltoids is only at about 21% [28].

The stride, or early cocking, is the second phase of the sequence, where the knee of the lead leg is pushed down while the leg is extended out, properly positioning the trunk for the rest of the pitch. The pitching arm is held back in the same position as in the wind-up, but the rest of the body is opened up to once again face the target. The angle between the lead leg and the stance leg is referred to as the stride angle. During this motion, elbow flexion should be about

80-100 degrees. Approximately 50% of the resulting ball velocity at the release of the pitch is due to resultant forces from the trunk rotation during this phase [6].

Following the stride phase is the late cocking phase, starting when the foot of the lead leg makes contact with the ground. This phase ends after the elbow is fully cocked back, and the shoulder is at a position of maximum external rotation. During the late-cocking phase, the shoulder is abducted from 90 to 110 degrees, while also externally rotated from 50 to 185 degrees. While this occurs, the long head of the bicep works to externally rotate the humerus past 60 degrees and flex the elbow. The external rotation is limited by the varus torque that is produced by the ulnar collateral ligament (UCL) in combination with pronators and flexors in the forearm [6].

The acceleration phase of the pitch begins when the shoulder is at maximum external rotation. The entirety of this phase only lasts about 42-58 milliseconds, which is one of the fastest physical movements recorded in athletics. During this phase, the trunk is rotated to bring the pitching arm forward with the hand following behind the elbow. The kinetic chain springs from a strong base of firmly planted feet, flowing up to the pitching hand at maximum external rotation. This stance creates a backwards “C” shape with the body. To finish the full rotation of the phase, the shoulder is snapped forward from external maximum external rotation to an internal rotation at over 9000 degrees per second. During this motion, the elbow is also rapidly shifted forward at about 2251-2728 degrees per second. After the pitching arm has fully rotated forward, the ball is released. At this point, the elbow is extended at 25 degrees, the shoulder is rotated internally, and the wrist is pronated to 90 degrees [6]. The maximum amount of varus torque at the elbow is experienced during this phase [21]. This torque is due to the muscles controlling the position of the elbow in the forearm; the flexor pronator muscles display especially high activity late during the acceleration phase [7].

The deceleration phase of the pitch occurs after the ball has left the hand of the pitcher. The pitcher follows through the forward motion of the throw by raising the stance leg off the ground and transitioning to full weight balanced on the lead leg, while bending the knee of the lead leg forward. The trunk rotates over this leg, and the pitching arm follows across the body. At the end of the motion, the shoulder is both at maximum internal rotation and 35-degree horizontal abduction. The activity of the shoulder and elbow muscles are lowest during this phase. A large part of the balance required both during this motion, and after when returning to a

fielding stance, comes from the internal flexion of the lead side hip, which is supported by the teres minor, infraspinatus and posterior deltoid muscles around the humerus, and the serratus and rhomboids around the scapula [6]. However, an underdeveloped or injured rotator cuff can cause overcompensation during the deceleration of the pitching arm through an increased horizontal flexion at the trunk [21].

## 2.3: Elbow Injury Statistics

Elementary and developing baseball pitchers are at high risk for elbow injury [1]. In 2014, it was reported that 4.34 million children between the ages of 6 to 12 years participated on a baseball team and although this is a decrease of one million from the number of children playing baseball in 2007, the number of youth pitching injuries reported in recent years is actually on the rise [21]. It was reported in 1998 that between 18-45% of youth pitchers experience some level of elbow pain while playing baseball [3]. From a more recent perspective, about 26-51% of youth pitchers report general arm pain during the 2018 spring season [21]. Five percent of youth pitchers will suffer from shoulder or elbow injuries that either require surgery or end their ability to play baseball [1].

The percentage of baseball players at the youth and high school level who have had UCL injuries requiring surgery has increased from 0% in 1994, to 31% in 2010 [1]. There has been a 50% increase specifically in the number of high school baseball pitchers requiring UCL reconstructive surgery, and most of these injuries occur in an instant, with no warning signs [2]. In a case study by Fleisig investigating the number of elbow operations performed by a single sports surgeon over time, operations on high school players made up 11.4% of these procedures between the years of 1995 and 1999. This figure increased to 19.9% of the total elbow operations performed by the surgeon between the years of 2000 and 2004 [29]. A study done between 1995 and 2000 followed 27 high school baseball players that had a UCL reconstructive surgery, and revealed that 89% were pitchers. It was reported that 74% of the players were able to return to play at the level they were when the injury occurred after an average of 11 months [2].

Baseball pitchers at the collegiate level have an increased risk of elbow injury due to their prolonged exposure and overworking of joint stresses when compared to youth pitchers [2]. It was reported that 15% of college baseball players feel pain and tenderness in their elbow that results in limited movement, and most feel this is a result of their youth baseball pitching training



and experience [3]. One study analyzed 5295 collegiate baseball players, and found that 2.5% had surgery to repair a UCL injury over the course of one year [30]. The same case study by Fleising mentioned above also investigated elbow surgery incidences for collegiate players. The amount of collegiate elbow surgery patients of the surgeon increased from 38.6% of the total patients between 1995 and 1999, to 48.4% between 2000 and 2004 [29]. Interestingly, it has been reported that the surgery rate for underclassmen collegiate players is exceptionally higher, and almost double that, of upperclassmen collegiate players [30].

## 2.4: Pitching Injury Mechanisms

It is reported that about 26-51% of youth pitchers have complained of shoulder and elbow pain [21]. Improper pitching mechanics have been cited as one of the causes of this phenomena through poor technique [4]. Two critical instances of the pitch have been highlighted as the most dangerous points of injury mechanism: shortly before the shoulder reaches maximum external rotation during the late cocking stage, and shortly after the ball release during the deceleration phase [5]. However, there are risks of injury in each phase of the pitch [6].

The wind-up and stride phases have been reported to have lower levels of injury mechanisms than the following phases [21]. At the conclusion of the wind-up phase, the pitcher is at the balance point, as mentioned previously. If the pitcher does not position the center of gravity correctly, the timing in the sequence that makes up the kinetic chain will be skewed. When this imbalance occurs, the torques generated in the lower extremities will travel up the kinetic chain to the more distal segments, predisposing the shoulder and elbow to injury. After the wind-up, the proper execution of the stride primarily focuses on the movement of the pelvis, which is rotated between 400-700 degrees per second in this phase [6]. As with the risk of injury during the wind-up, an incorrect stride or position of the hips will impact the timing of the sequence of motion in the kinetic chain. This could cause an inefficient transfer of energy through the body, again predisposing the shoulder and elbow to injury [4].

During the late cocking phase, a varus torque is applied to the forearm at the elbow, primarily by the ulnar collateral ligament (UCL). This torque is in response to the valgus torque generated by the kinetic chain at the elbow, which can cause medial elbow injuries if the varus torque is not high enough. During a normal pitch of an adult professional baseball pitcher, it was reported that the varus torque is about 64 Newton-meters, and the UCL contributed 34.6

Newton-meters of this. However, cadaveric testing of the UCL has shown a maximum producible torque of 32.1 +/- 9.6 Newton-meters, meaning this stress causes the UCL to perform right at, or just above, maximum capacity [5]. Also, the correct position of the hand on top of the ball during this phase is important for correct shoulder abduction during acceleration. If the hand is slightly under the ball instead, the shoulder will have a delayed abduction that will result in the pitching arm being late in the rest of the pitch in relation to the body, which can cause an extreme horizontal abduction at the shoulder and possible injury [4].

As with the late cocking phase, the acceleration phase also generates a large amount of varus torque to resist valgus torque [5]. A common mistake within pitchers is to track a sidearm throwing motion during this phase. This motion can cause the generated valgus torque to primarily overwhelm the UCL, among other medial elbow structures, contributing to a cumulative microtrauma [6]. The injury mechanisms in the late cocking and acceleration phases are very significant, as elbow injuries, primarily focused around the UCL, are the most common cause of injury time loss for collegiate pitchers [31].

The follow through in the deceleration phase is critical in transferring the forces and torques through the kinetic chain correctly. If the motions in the follow through are not timed correctly, this transfer of force can be damaging. It has been reported that up to 1090 Newton's of compressive force occurs at the shoulder joint just after ball release. Improper form at this point can cause an overcompensation of the rotator cuff. At this level of stress, overuse of the rotator cuff can result in tensile failure [5]. Also, the eccentric motion of the posterior musculature at this point, that is required to assist in dissipating these high levels of force, can contribute to the development of glenohumeral internal rotation deficiency, leading to further problems at the shoulder joint [6].

## 2.5: Elbow Injury Repair

After a potential elbow injury has occurred, immediate physical evaluation is necessary. There are three main physical tests a physician can administer to determine the condition of the medial elbow structures, focusing specifically on the ulnar collateral ligament (UCL): a valgus stress test, an anterior bundle posterior band stress test, and a moving valgus stress test [31]. To achieve full recuperation from injury, UCL repair can be executed in two ways: rehabilitative or surgical. Both rehabilitative and surgical routes of recovery are costly and require time and

cooperation from the patient. To ensure for a complete and healthy recovery, rehabilitation processes are necessary for both initial injury treatment as well as postsurgical recovery [32]. Athletes who undergo nonoperative means of elbow treatment return to playing in 42% of cases [31].

The most common surgical procedure for UCL repair is an ulnar collateral ligament reconstruction (UCLR), using some variation of the Jobe technique [32]. Typically, a UCL graft is used to help repair the ligament. It has been reported that 83% of Major League Baseball pitchers who received a UCLR were able to return to sport [31].

After surgery, it is vital to the UCL healing process that patients be placed on a strict rehabilitation regiment [31]. Rehabilitation of elbow injuries does not focus solely on the elbow, but incorporates the muscles in the entire upper body, core, and legs to ensure there is proper healing and rebuilding within the joints. An initial assessment prior to rehabilitation is done to establish the physical state of the elbow prior to injury to determine realistic restoration results and an adequate regimen [32]. There is a progressive order that elbow rehabilitation must follow, and is broken down into four phases [31].

The first phase of rehabilitation focuses on promoting healing, while also preventing stiffness from building up in the medial elbow structures [31]. The activities done in the first phase include range of motion exercises in the elbow and wrist to help with cartilage and collagen tissue nourishment [32]. Phase two of the rehabilitation process focuses on maintaining previous progress and to further develop elbow joint mobility, muscle strength, and control. In this phase, stretching exercises continue and mobilization techniques can be increased in intensity to further stretch the tissues, mainly in all three joints of the arm, and avoid a plateau of progress. The third phase is called the advanced strengthening phase and focuses on gradually increasing the strength, endurance, and control of the elbow. The strengthening activities in this phase are set at a higher resistance and are typically functional movements and eccentric contraction by elbow flexion exercises. Also, athletes will be placed under a sport-specific plyometric program towards the end of this phase; baseball pitchers will be taught proper throwing mechanics, with their motions reviewed [31]. The fourth and final stage of the rehabilitation process is the return to activity phase. This phase, as it states in the name, is meant to make the final steps of progress for the athlete to return to competitive activity through a progressive interval program [31]. The intensity of the intervals in this phase increase

proportionally by 10-25% increments of the athlete's progress, and most pitchers with elbow injuries begin at 50% intensity. The intervals each include a stretching exercise, one exercise set, an overhead activity, and two more exercise sets. Once this phase is completed, the athlete is considered ready to return to playing competitively, or at the point they were at before injury [32].

## 2.6: Current Market Devices and Preventive Strategies

There are several market devices and preventive strategies designed to provide feedback to athletes on their activity and reduce injury risk. Current market devices and preventive strategies can be broken down into three main categories. These three types of preventive techniques are stretching and strengthening exercises, video and motion analysis applications, and braces. Stretching and strengthening exercises can be used to improve the range of motion and pitching mechanics in general. Video and motion analysis applications can be used by the baseball pitcher to develop a proper pitching technique and improve biomechanics. Elbow braces are ideal for stabilization of the joint to avoid injury by overextension or excessive forces. These three current market devices and systems may decrease the chance of injury, but they lack certain aspects and could be greatly improved for the consumer needs.

### 2.6.1: Stretching and Strengthening Exercises

At the youth level, studies on pitching biomechanics assert that young pitchers should learn proper fastball technique. There has been a proposed stretching and strengthening protocol called the Yokohama Baseball-9. Each exercise, performed for 10-seconds, is meant to improve posture and range of motion in the elbow, shoulder and hip. In the cohort of players who participated in this stretching regimen had about 50% fewer medial elbow injuries, evaluated during a 12-month follow up. Moving forward to the collegiate level, it is important to continue to emphasize proper pitching mechanics [11].

Driveline Baseball is an in person or online program that uses player-specific data to determine the development process. The program consists of tracking data in three phases: testing, training, and retesting. The test portion is there to get preliminary results and decide where the player will begin the program. The train portion is the actual development phase where the athlete is participating in activities to better their performance. The retest phase is there to

check that the program is working adequately to achieve the initial desired results. The retest is also in place to make any modifications to the program if there are any issues found. The program uses equipment such as motion-capture and high-speed video, barbell speed tracking, and ball flight tracking. This equipment is used to capture data and create an individualized profile for the athlete. This profile ultimately outlines the developmental program. The program created for each athlete is similar in the ultimate goal of correcting mechanics to improve results and reduce the risk of injury. Driveline Baseball has a location in Seattle, Washington but also has other resources to aid players at off-site locations. Some of these other resources include online pitching and mobile pitching assessments. All Driveline Baseball programs can be altered to be used at beginner, youth, and more advanced levels, further emphasizing the individualized aspect. The programs provided by Driveline Baseball are expensive and have a cost range from \$250-\$1440 [33].

## 2.6.2: Video and Motion Analysis Applications

Developing pitchers can find assistance with their mechanics through visual resources. These include videos found on YouTube and also motion analysis apps. Major League Baseball (MLB) pitchers of various backgrounds and styles of pitching mechanics have been posting helpful videos on YouTube to assist developing pitchers looking to improve their form. A simple search for “baseball pitching mechanics” on YouTube will provide an interested person with copious amounts of helpful videos. Some of the most notable posters include Justin Verlander, Marcus Stroman, Aroldis Chapman, and Trevor Bauer. Verlander is considered to be a pitcher with very efficient mechanics in the MLB. Stroman has a height of 5 feet 8 inches, which is considered short in the MLB, and has developed a pitching form to maximize his throws regardless of his small stature. Chapman is recorded to have the fastest pitch in the MLB at 105.1 MPH, and has specific mechanics to allow him to achieve this high speed without risking injury. Bauer participates in Driveline Baseball programs to improve his mechanics, and often shares his progress and form to help other developing pitchers. By watching the mechanics and process of pitching through videos of experts, the audience can use this information to attempt to correct their own baseball pitching motion. The limitations of this strategy is that the videos can be difficult to correctly interpret and implement to someone’s preexisting techniques, as well as being a more subjective technique.

There are a number of smartphone apps which guide players on preparation and training. “Throw like a pro” is an application released in 2014. The aim of the application is to improve strength, enhance endurance and flexibility, while also strengthening the core muscles used in throwing. There are two primary sections in the app which actually pertain to the player’s injury prevention: pre-season preparation (which uses a strengthening program called “Thrower’s Ten” and guided stretching), and in-season (guiding warmups, pitch counter and behavior avoidance). Groups of athletes were assessed for injury rates, the athletes were split into two groups: high and low app compliance. The high compliance group experienced a decrease in throwing injuries in comparison to a control group [34]. These apps are ideal for preparing the joints and muscles for the throwing motion, but they do not alter or improve the mechanics of the pitching motion which can lead to injury.

Video analysis applications, such as “Hudl Technique”, can be used on smartphones to record an individual during their motion [12]. This recording can be watched later and placed side-by-side with videos of a pitcher’s motion that is considered accurate and correct [12]. The observations found from seeing visual differences between the two pitching motions can be used to determine any alterations that can be made to the mechanics to improve the overall results and reduce the risk of injury. The issue with these video analysis applications is that they lack the ability to give the pitcher real time feedback, meaning corrections to the pitching mechanics cannot be made immediately. Most of the video analysis applications currently on the market are offered to pitcher free of charge, but more advanced technologies may require a low cost fee.

### 2.6.3: Braces

Various braces are currently on the market to help prevent injury in the elbow, specifically injuries involving the UCL. Don Joy Performance provides multiple types of braces to suit specific consumer needs [35]. There are three main types of support provided by the different types of braces. The highest level of support is their Bionic Elbow Brace, which prevents elbow hyperextension for injured elbows or elbows recovering from surgery. The medium support level brace is the Trizone Elbow Support brace, which provides support during activity to avoid overworking the joint. The lowest level of support is with the Elastic Elbow brace, which is a simple elbow compression sleeve to reduce elbow pain [35]. The Don Joy Performance braces range from a cost of \$12.49 to \$79.99 depending on the support level [35].

The Bauerfeind Sports Elbow Brace, previously called the EpiTrain PowerGuard, is another elbow brace designed to avoid hyperextension in the joint [13]. This brace stops the arm from reaching full extension at the end of the pitch, without limiting the arm's range of motion. The brace works by using a dial to tighten the brace to the desired support or control level [13]. By avoiding the full extension of the arm, there is no valgus overload which translates to a reduced risk of overextending and harming the joint. This brace is primarily used in post-operative stages, and is not considered a preventive device [13]. Although these braces aid in preventing harmful motions and supporting the elbow joint and ligaments, it does not adjust the pitching mechanics of the player meaning there is no improvement being made to the user's biomechanics. In other words, the braces assist injury prevention in the moment but future pitching situations will not be improved and injury is likely to occur if the pitcher has been dependent on the braces. The Bauerfeind Sports Elbow Brace can be acquired for a price of \$199.99 [13].

The mThrow from Motus is a wearable sensor device which claims to track the strain on a pitcher's elbow, monitoring workloads, and mechanics. The mThrow consists of a compression sleeve with a small sensor positioned over the elbow. The sensor's accelerometers and gyroscopes monitor arm movements and calculates the stress caused by torque on the UCL. The benefit of this brace is that it is immediate to the player and can be used during any practice, releasing the player from relying on once or twice a year motion capture assessments [14]. Although the data provided by the Motus brace is immediate, it must be downloaded to an external app. The data provided also does not give the pitcher feedback on ways to improve form if they are considered in danger of injury. From the Motus webpage, the mThrow by Motus along with other packages can cost anywhere between \$149.99 to \$2000.

#### 2.6.4: Current Device Market Gaps

Although there are many available devices currently on the market, none of them adequately improve and correct the baseball pitching mechanics that lead to injury. The primary issues revolving around the current devices and the market gaps include the inability to give real time feedback, the inability to provide comprehensive feedback, and the inability to provide subject specific feedback.

The video analysis applications can improve pitching form in later reviews, but do not give real time injury prevention feedback [12]. The mThrow brace from Motus provides quicker feedback, but the data is downloaded through the mobile application once the practice or game is completed, meaning that there is no real time injury prevention [14]. The feedback provided by the Motus, including forces and torques experienced by the elbow, is a report of raw data which cannot be easily interpreted by most players. This ultimately means that the subjective data provided does not establish a way to improve the pitching mechanics when potentially harmful stresses are being experienced in the elbow.

Stretching and strengthening exercises can be used to reduce baseball pitching injuries, but they primarily prepare the arm for throwing instead of avoiding potentially harmful torques in the elbow [11]. Motion-capture applications also do not prove injury prevention comprehensive feedback because they are reviewed once the pitch is completed, and an interpretation is made based on a comparison of the user's technique with a standard technique. It is difficult to determine if technique and biomechanic form is correct solely based on visual interpretation, and is subjective to the user.

The elbow braces currently on the market are non-subject specific and are not individualized to meet the specific pitcher's needs. Each pitcher has their own form of mechanics that work for them, and these braces do not adjust accordingly. Motion limiting braces impede the natural motion of the arm during a pitch meaning they lack the customization aspect [13]. The mThrow by Motus provides generalized feedback to determine healthy ranges of data, but the device is not calibrated to the user meaning that there is no way to tell if the feedback is accurate for the individual [14].

## 2.7: Injury Prevention Research

Wearable sensor systems are popularly used in the tracking of biomechanics, understanding mechanisms of injury, and teaching proper biomechanics. An early 2010 study using accelerometers placed on the forearm and upper arm of baseball players aimed to show that these sensors could provide a similar level of accuracy to optical motion capture systems in determining the acceleration and angular velocity of the elbow. The sensors were consisting of both an accelerometer and gyroscope. A challenge in the selection of the sensor components was compensating for the measurement ranges for acceleration and angular velocity during pitching,



400 meters per second and 2000 degrees per second respectively. Two sensor locations provided enough information to determine the accelerations and angular velocities of the forearm, but left it difficult to interpret the motion of the upper limb [9].

A more recent study applied a single sensor to the subject's upper arm to focus on the detection of upper arm athletic motions (baseball throwing and serving in volleyball). The research team set about the task of discriminating throws and serves from other motions. The algorithm for identification searches for data segments where the elevation of the arm is greater than 45 degrees and then angular rate is greater than 400 degrees per second [10]. The goal of this study was to classify the actions and select the appropriate segment of data around the instance for optional further analysis. However, shortcoming of this study in terms of the biomechanics, is that all angles are relative to the ground, rather than with respect to the body, so it is possible that these identification criteria may vary within pitchers.

The previously mentioned Motus mThrow sensor is an inertial measurement which reports the angle of the forearm relative to the ground at the release of the pitch (arm slot), the speed of the arm, as well as shoulder rotation and elbow stress. A 2018 study used the Motus mThrow to observe elbow stress variation as a method of indicating fatigue, and by extension potential injury resulting from variation in elbow biomechanics. The study was conducted by collecting the Motus generated data. The results of the study demonstrate variability in varus torque during pitching, from warmup to bullpen sessions. The subjects however did not pitch until fully fatigued, so the data do not show torque variation resulting from fatigue, but it is suggested in the study that the comparison of fatigued pitching, when compared to established mean values for the subject, would inform acceptable torque variations before injury is risked [36].

In running, studies have been conducted to observe kinematic change correlated to fatigue. One such study found that the regularity of movement decreased as levels of fatigue increased. In order to observe fatigue, researchers placed off the shelf inertial measurement units (IMUs) on limbs of interest of subject running at 85% of their individual maximum speed. The kinematic changes in the runners were noted as fatigue increased. These changes indicated more mechanical variation and decreased physiological economy, placing increased stresses and strains on the body [37].

From analyzing the anatomy of the elbow joint as well as the mechanics involved in baseball pitching, elbow injuries such as UCL injuries are a recurring problem. The elbow injuries have been documented in all levels of baseball including youth, high school, collegiate, and professional. Currently there are techniques to assist in limiting the injury risks including muscle stretching and strengthening, video motion analysis, and braces. The current market solutions to baseball elbow injuries require improvements including real-time feedback and subject specific analyzation incorporated into an easy to use system.

## Chapter 3: Project Strategy

This chapter outlines the goals of the project, justifications for these goals, and the resulting criteria used for design requirements. The process used for this approach starts with the formation of an initial client statement, followed by definition of requirements broken down into objectives and constraints. From this, appropriate design standards were reviewed. Ultimately, a revised client statement was defined to outline the project approach.

### 3.1: Initial Client Statement

The scope of this project follows from the initial project statement provided by Dr. Magit and Professor Karen Troy, the project sponsor and project advisor respectively:

Design and develop a system to measure baseball pitching biomechanical loads in the arm for the purpose of elbow injury prevention, with the following requirements and details:

1. *The system should be wearable,*
2. *The system should provide biofeedback for future injury prevention, and*
3. *The system should be non-subject specific with objective feedback.*

### 3.2: Technical Design Requirements

After the establishment of the client statement the following design requirements, including objectives and constraints, were developed.

#### 3.2.1: Design Objectives

- **Ease of use:** The system should be simple to assemble onto each user and require a simple calibration for individualized use. There should be minimal error that can be experienced by the user as well as in the analyzed data.
- **Adjustable:** The system should be subject-specific and allow for an accurate fit on a wide range of users. The adjustability of the system will allow the sensors to be placed in precise locations on the body to obtain more accurate results as well as a more comfortable fit for the user.

- **Accuracy:** The analyzed data from the sensors should produce feedback results within 80% of the laboratory standard. The data analyzed as well as the calculations used to provide the feedback output should be verified and validated through testing and calibrations.
- **Automated Analysis:** The system should contain a coding mechanism to interpret the raw data provided by the sensors to produce an automated feedback output. This automated analysis will serve as an indication of when unhealthy deviation from the baseline metrics is reached.
- **Feedback Time:** The system should detect the motion and complete the analysis programs within 20 seconds, which is the maximum time between the end of the previous play and the required pitch time, per the regulations of the MLB.
- **Wearable:** The device should be easy to apply correctly to the subject with minimal training, and remain on the body despite motion or perspiration for a minimum of 4 hours, which is one hour longer than the average game will last.

The pairwise comparison chart shown in Table 1 below displays the needs of the system and their respective rankings. Based on the rankings, the team decided that it is most important to focus on an accurate and wearable system.

*Table 1. Pairwise Comparison Chart of System Needs.*

<b>Requirements</b>	Accuracy	Adjustable	Ease of Use	Wearable	Automated Analysis	<b>Total</b>
Accuracy	X	1	0	0	1	2
Adjustable	-1	X	-1	0	1	-1
Ease of Use	0	1	X	-1	1	1
Wearable	0	0	1	X	1	2
Automated Analysis	-1	-1	-1	-1	X	-4

### 3.2.2: Constraints

- **Time:** The project should be completed within the time of the academic year, spanning from September-April. A prototype of the system should be presented by December 14th, and validation testing should be completed by March 1st.
- **Cost:** The budget for this project is \$750, as allotted by the institute.
- **Off-the-shelf sensors:** The system will rely on the use of off-the-shelf sensors. Therefore, it is necessary to find sensors which best fit the measurement ranges of the system. These measurement ranges will be defined in the following sections.
- **Software:** The sensors in the system will not only collect and store data, but also interpret the collected data to output intuitive feedback. The system therefore should be compatible with the project code written in MATLAB script.
- **IRB approval:** This project will involve the use of voluntary human subjects for research and testing, requiring testing procedures to be approved by the WPI Institutional Review Board (IRB). All testing with human subjects used for system development and validation should comply with guidelines concerning ethical and regulatory concerns to mitigate risk for the voluntary subjects.
- **Limited set up time:** The sensor setup time should be minimal so that the system is easy to use and does not interfere with the activity monitored. The hardware of the sensor system should take less than 10 minutes to put on and properly calibrate.
- **Limited interference:** The sensor system should not impede the motion of the player's pitch, and should not cause discomfort during use. Restriction of any of the natural movements of the pitch will result in inaccurate results.

### 3.3: Standards for Design Requirements

The sensor system the team will develop in the project will include medical research employing voluntary human subject testing. Several different standards agencies have requirements that will need to be adhered to in the design of the system, including organizations such as: The Food and Drug Administration (FDA), the International Organization for Standardization (ISO), the Institute of Electrical and Electronics Engineers (IEEE), and the

Federal Communications Commission (FCC). The standards from these organizations concerning an electronic, wearable device for medical diagnostics are detailed below.

- **FDA:** Because no concrete medical claims are being made, there will be no need for FDA approval at any level for the use and distribution of the device.
- **ISO:** This device falls under six categories of ISO standards. These standards include the following requirements:
  1. ISO 13485, Medical Devices -- Quality management systems -- Requirements for regulatory purposes
  2. ISO/IEC 17025, Testing and calibration laboratories
  3. ISO/IEC 27001, Information security management
  4. ISO/IEC 29182, Information technology -- Sensor networks: Sensor Network Reference Architecture (SNRA)
  5. ISO 14155, Clinical investigation of medical devices for human subjects -- Good clinical practice
  6. ISO 21500, Guidance on project management
- **IEEE:** IEEE P360 is the standard for wearable consumer electronic devices, providing the specifications that define the technical requirements and testing methods for wearables. These include security and suitability of wear, and ranges to functional areas such as health and fitness.
- **FCC:** A wearable is defined as including a digital tool that can be worn and may also help to improve athletic performance and prevent injuries. For wireless devices all communication between device and controller should be between 402-405 MHz or by Wi-Fi or Bluetooth.

### 3.4: Revised Client Statement

From the technical and standards driven requirements, the following client statement was revised and decided upon. Based on the understanding that increased fatigue leads to greater variation in pitching motion, which leads to increased risk of injury:

The goal of this project is to develop a low profile wearable sensor system for pitchers to use during games and practice sessions. The sensor system will measure the forces and torques at the shoulder and elbow during the pitch through a system of two IMUs. The system will analyze

these measured data to identify variation from the individual's baseline motions to then indicate fatigue through deviation from the baseline. The device will provide easy to interpret feedback to coaches and pitching staff, enabling them to determine when athletes are reaching a point of fatigue that places the athlete at increased risk for injury.

### 3.5: Project Approach

**Aim 1:** *Determine metrics of interest to be analyzed and develop equations of motion.*

To determine the metrics of interest to be analyzed in the system, research will be conducted on baseball pitching UCL related injury literature. From the team's research, an initial design concept will be developed to quantifiably predict the risk of injury. Based on the initial design concept, the main metrics involved in UCL injuries will be determined to be analyzed in the system. After determining the metrics of interest, models will be created to display all the variables that would be acting on the arm during a baseball pitch. The models will be in the form of free body diagrams, and the arm will be segmented into two parts: the upper arm and the forearm. From these models, equations of motion will be developed to calculate the metrics of interest from raw data inputs. These metrics of interest will then be able to be analyzed further. These models and equations of motion will then be used to create a working system.

**Aim 2:** *Create a low profile wearable measurement system that players can wear during practice and game play that can identify variations in biomechanics associated with fatigue.*

The system will use in-subject and in-session variations in the raw data to identify fatigue. Two small wireless IMUs will be adhered to subjects' body on the upper and lower arm segments. Using the software component of the system, the team will use the raw data from the sensors and the developed equations of motion to calculate the metrics of interest for the pitcher within that session. The software component will also determine the extreme values for each individual pitch in order to compare the pitches to each other more effectively within the session. These pitch values will be grouped in windows to compare the variability of the pitches against one another. Through the use of the software, a healthy baseline and variability will be established using the in-session data. The software will compare the subsequent pitches against the baseline to flag potential fatigue.

**Aim 3:** *Conduct human subject testing to assess the system's ability to measure fatigue.*

After the creation of the system, the team will conduct human subject testing. The data from these sessions will allow the team to assess the system's ability to measure fatigue. More specifically, the goals of the human subject testing include: gather field data from pitching practices to test the abilities of our code, use the system in real-world operating conditions to analyze any hardware limitations, test the feasibility of the system's operation protocol, and conduct usability testing to assess the practicality of the physical system. To accomplish this, the team will design and facilitate three human subject testing protocols: baseline data collection where real world pitching values are collected, induced arm fatigue data collection where fatigued data is collected, and a usability study where data is collected concerning the feasibility of the physical system. Following the human subject testing, the data collected will be processed, analyzed, and used for further system validation testing.



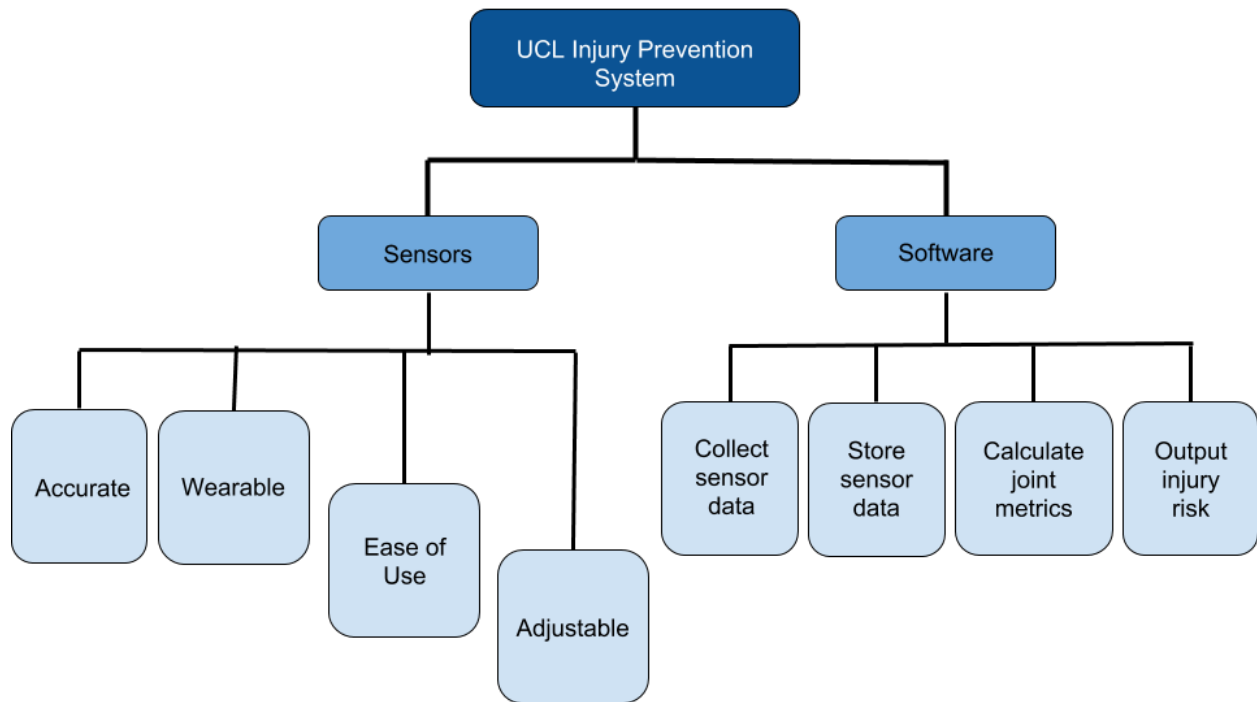
## Chapter 4: Design Process

The following chapter outlines the process of creating conceptual designs based on specific needs outlined by an analysis of the problem statement as well as required specifications. This chapter outlines the components that fulfill the system's needs and specifications as well as developments made from the preliminary conceptual designs. These developmental designs were tested through experiments to ultimately make decisions regarding a final design for the system.

### 4.1: Needs Analysis

Based on the client statement and requirements outlined by Professor Karen Troy and Dr. David Magit, the team conducted a needs analysis to ensure all requirements were met in the development of the system.

The requirements outlined in Chapter 3 of this report include an elbow injury prevention system that is wearable, provides easily interpretive biofeedback, and is non-subject specific with objective feedback. After research, the team decided the best solutions for this system for the purpose of data collection would be a set of wearable motion sensors, due to their ability to track movement as well as collect data and metrics as in the previous chapter. A motion sensor is also capable of not only collecting and storing the data, but also transferring it to a software for objective analysis. To accomplish the system requirements, the sensors and software must have certain components and capacities. The sensors within the system must have the capacity to collect raw data capable of being used to measure the forces and torques of the shoulder and elbow joints during the pitching motion. The sensors must measure with an adequate level of accuracy, thus a certain sampling frequency and consistency in data capture is required. The sensors must also be adjustable to each subject and easy to use. The software within the system must have the capacity to collect and store the data from the sensors, analyze the data using calculations for the forces, velocities, and torques in the joints, and finally display the elbow injury risk results. All of these needs and requirements for the system have been categorized in Figure 3 below.



*Figure 3. Needs and requirements hierarchy for the proposed system. Importance of needs is indicated by height.*

## 4.2: Alternative Designs

During the preliminary design phase four main concepts were brainstormed in response to the initial and revised client statements. Here we will outline these main concepts and rationalize the decision to or not to continue to develop the concept into the final design.

### 4.2.1: Video Capture

The initial design concept was based on a video capture methodology. Throughout the pitch a kinetic chain is followed fairly consistently across different pitchers, meaning that various body positions will be achieved as the pitch progresses. By placing a small camera in front of home base and equipping the pitcher with fiducial markers at specified physical landmarks (i.e., styloid process of the ulna, medial epicondyle of humerus, acromion process, and the ASIS), it would be possible to see if the kinetic chain is being followed accurately. Identifying

deficiencies within the kinetic chain of a pitcher could identify possible causes of strain for the pitcher which may lead to injury.

The primary drawbacks to this concept are the lack of individual subject calibration and the delayed feedback. It would be difficult to define a baseline of normal for each subject in this system, without initially collecting large amounts of data. Because this is not an immediate form of feedback, this system would be limited to use as a training device. Another difficulty to the system is that, similar to current systems, it would require expert analysis to be fully and accurately interpreted. With this form of analysis there is known subjectivity, wherein different pitching coaches will interpret the motion differently and provide varying feedback. Therefore, even if the data analysis could be automated, the corrective feedback may be biased and would still be delayed. In addition, automating the feedback would require a level of consistency between players that would be difficult to account for, from this perspective it would be difficult to provide relevant and custom feedback to players. For these reasons, we did not elect to continue to develop this concept.

#### 4.2.2: Constraint Brace

The second design concept was a constraint brace, which would prevent injurious elbow motion or configurations. Many UCL injuries are the result of an unnatural or abnormal use of the elbow. The cause of this abnormal use is variable, but it may result in excessive loading, torque or extension being applied to the UCL. The brace would mimic the anatomy of the elbow to assist the internal mechanisms, while also containing mechanical stops, which would come into effect if the subject's elbow began to extend past normal or healthy positions and enter an injurious configuration.

A potential danger to such a design considers the kinetic chain. If the pitcher does not change his pitching mechanics and the only change is use of this constraint brace, then it is possible that the injurious loads will be translated from the elbow to the shoulder or wrist instead. This translation of the forces from the elbow could create new problems and cause new injuries. This is always an important consideration when stabilizing or immobilizing a joint in any capacity. Additionally, if the mechanical stop is too rigid, there could be negative ramifications of the constraint, but if the stop is too soft or flexible, the mechanism may not overcome the forces of the elbow. An additional problem associated with the brace is how to

accurately customize the range of motion. Injurious configurations of the elbow may vary between subjects, and customizing the constraints for each subject would require external expertise and work on behalf of the user. Finally, a device such as this may not be allowed in game play, where it would be most effective, making its purpose obsolete. For these reasons, we did not elect to continue to develop this concept.

#### 4.2.3: Biofeedback Brace

After determining that the constraint brace design may result in other injuries in the joints surrounding the elbow we considered a biofeedback brace instead. Similar to the constraint brace, this device would be able to detect potentially injurious movements and configurations of the elbow. However, instead of constraining the motion, the device would provide a small sensory feedback such as a vibration. The benefits of this would be real time feedback without impeding the motion. The pitcher would be able to know that the previous pitch was or was not potentially injurious, and make immediate self-corrections in the following pitches.

The drawback to the design is that the sensory feedback would not specify what about the motion made it potentially injurious, making it difficult for the pitcher to correct his future motions. Similar to the constraint brace design, calibrating the device would be a difficult task as the limitations would need to be set based on the individual's anatomy, therefore the injurious configurations would need to be determined. Additionally, the nature of the device may relegate it to use only during training, which would limit its effectiveness in preventing injuries during games. For these reasons, we did not elect to continue to develop this concept.

#### 4.2.4: 3D Motion Consistency

The final design concept was a 3D motion tracking system which would analyze consecutive pitches for variation. Risk of injury is directly correlated with increased fatigue, and by extension decreased muscle control. Therefore, as an individual's risk of injury increases, their movements should become less consistent. By placing 3D motion capture sensors on and around joints of interest, such as the forearm, elbow, upper arm, and shoulder, we can collect data and compute values such as the forces and torques at the joints. Because the data is all digital, objective automatic analysis between repetitions of the motions can be conducted to understand how the motion has changed overtime to identify fatigue or risk of injury.

The benefit to this design is automated analysis that is founded in subject and session baselines (i.e. the first 10 pitches of a practice, warm up, or game). Thus it is not necessary to determine what is universally normal or healthy, rather all that must be determined is how the current pitch compares to a healthy pitch based on standard deviations and average values. Additionally, the calculations are objective and do not rely on expertise on the end of the user or coach regarding the motion, making it easy to interpret the results and subsequently determine a course of action. Finally, the minimalist physical design components of the system would make it possible for the system to be used during gameplay, making it possible for coaches to objectively determine their player's risk of injury during the game and take educated preventive measures. For these reasons, we elected to continue to develop this concept.

The preliminary design is the use of electromagnetic tracking, or EMT, sensors on and around the joints of interest. These sensors will output raw data to be analyzed by a data analysis system such as MATLAB. The analysis will include calculation of the previously mentioned metrics and a systematic comparison of pitches to the baseline for the current session. The comparison to the baseline will quantify fatigue through the calculation of the average and standard deviations of each pitch extreme value. Ideally the analysis can occur immediately following the pitch so that the coaches can make the game time decision to remove a player who is indicating injury risk.

## 4.3: Design Requirements and Functions

After the needs of the system were analyzed by the team, the specific component requirements were outlined. The requirements determined for the system include specifications for each part of the system, broken down into sensor requirements and software requirements.

### 4.3.1: Sensor Requirements

The sensor system designed by the team will be used as a motion detection and tracking system for the throwing arm during a baseball pitch. The inputs for the system will be motion over time. The outputs from the system will be motion in three degrees of freedom and rotation angles in three degrees of freedom over time. Based on the needs analysis outlined above,

requirements for the hardware of the system were outlined. The requirements for the hardware used in the sensor system are detailed in Table 2 below.

*Table 2. Sensor Subsystem Requirements.*

Requirement #	Requirement
R001	The motion sensors shall record accelerations up to +/- 16 G's
R002	The motion sensors shall record motion up to an angular rate of 2000 degrees per second.
R003	The motion sensors shall record motion in six degrees of freedom; three translational and three orientational axes.
R004	The motion sensors shall have a sampling frequency of at least 120 Hz.
R005	The sensor system shall operate for a minimum of four hours straight.
R006	The system of motion sensors shall weigh less than one pound.
R007	The motion sensors shall securely mount onto the body of the user.
R008	The sensor system shall store motion capture data locally.
R009	The sensor system shall report back motion and time coordinate outputs in I <sup>2</sup> C.
R010	The motion and time coordinates of the sensor system shall interface with the data collection interface written in MATLAB code for analysis.

#### 4.3.2: Software Functions and Requirements

Assuming that the sensor system requirements are met, the data then must be interpreted through software to model the pitching arm in space in relation to the body. From this, the velocity and angular acceleration of the elbow is used to calculate the varus torque at the elbow. Baselines for the values and standard deviations of force and torques at the elbow and shoulder

for the user will be established. The calculated biomechanics from each pitch after baseline establishment will be compared chronologically using a sliding window analysis to observe the change in standard deviation of varus torque over time. An increase in standard deviation of a specified value will indicate that the user has become fatigued to a level where there is an increased risk of elbow injury, informing the user to stop pitching. An overview of the software developed for the sensor system is detailed in Table 3 below.

*Table 3. Software Subsystem Overview.*

Inputs	Linear Acceleration (+/- x, y, and z axes) in meters / second / second
	Angular Velocity (+/- azimuth, elevation, and roll) in degrees / second
	Time values in milliseconds
	Subject Specifications (Height, weight, arm lengths, sensor location)
Source	The raw data from the sensor system will be stored in a comma separated values (.csv) file that is uploaded into the MATLAB code
Outputs	A cell array for each sensor at every time point containing the recorded linear acceleration and angular velocity values.
	Appended cell arrays where missing data points from each array have been eliminated from all arrays to ensure continuity between the data sets.
	Force at the elbow and shoulder.
	Torque at the elbow and shoulder.
	Range of Torque.
	Standard deviations of torque over time in a window with a width of 10 pitches and height of the range of torque values.

	Pass/fail indication of dangerous injury risk (pass indicates healthy variation, fail indicates dangerous variation of varus torque).
Destination	A local database in the form of a .csv file.
Pre-condition	The MATLAB script must be open and displayed on the user's screen.
Post-condition	The raw data .csv file is unchanged, and a new .csv file of calculated values is stored locally on the user's computer.

From the constraints of the software overview, detailed requirements were created. The requirements for the software used in the sensor system are detailed in Table 4.

*Table 4. Software Subsystem Requirements.*

Requirement #	Requirement
R011	The software shall receive raw data from the sensor system in the form of a .csv file
R012	The software shall create cell arrays of continuous acceleration/angular velocity/time data across all sensors
R013	The software shall calculate the angular acceleration of the arm segments during a baseball pitch
R014	The software shall calculate the overall force at the elbow during a baseball pitch
R015	The software shall calculate the overall torque at the elbow during a baseball pitch
R016	The software shall indicate to the user when the standard deviation of overall force at the elbow implies a dangerous level of injury risk
R017	The software shall indicate to the user when the standard deviation of overall torque at the elbow implies a dangerous level of injury risk



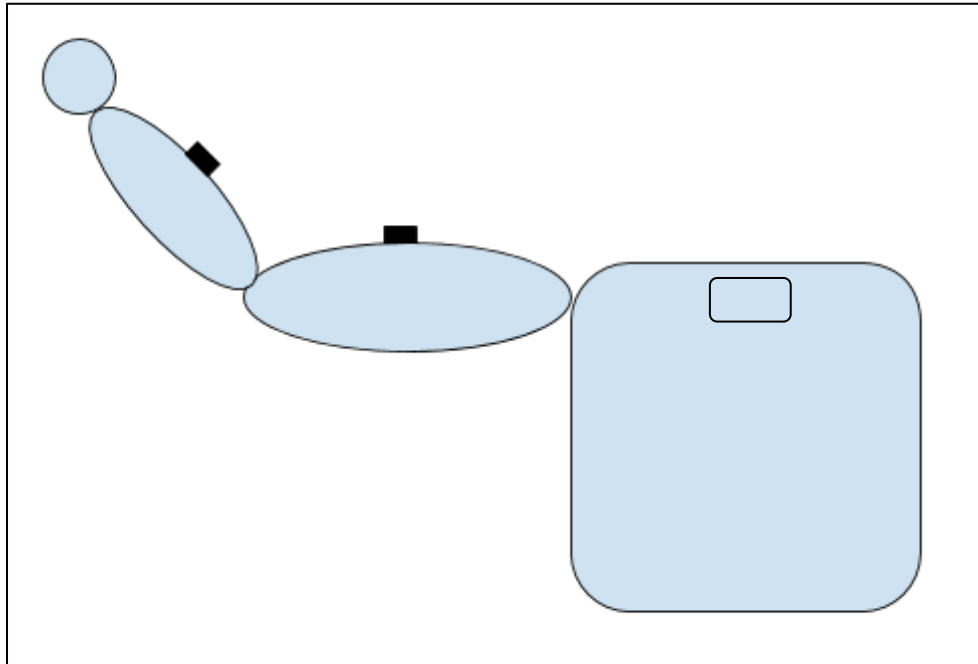
## 4.4: Conceptual Designs

Based on the hardware requirements outlined in Table 1 above, the team proceeded to select candidates for the sensor system. A variety of sensor units were selected to then compare and contrast the benefits of each option. The potential sensor units reviewed by the team are outlined below.

- Blue Thunder by IMeasureU: This IMU can measure accelerations up to 16 g's, and angular velocities up to 2000 degrees/second. These sensors come fully packaged, meaning the components are completely encased with a protective cover, making them durable. The Blue Thunder can both store data locally, as well as transmit data real time over Bluetooth to a compatible device, such as a smartphone or computer. IMeasureU offers a full software package that reads the data from the Blue Thunder. To acquire this sensor, a demo must be first scheduled with IMeasureU [38].
- 9DoF Razor IMU M0 by SparkFun: This device is a MPU-9250 motion sensor combined with a microprocessor all on a single breakout board. The IMU can measure accelerations up to 16 g's, and angular velocities up to 2000 degrees/second. The breakout board contains a micro SD card slot for local data storage, microUSB port for connection to a computer, and a lithium-ion battery charge port. The microprocessor comes fully loaded with the Arduino bootloader software package for simple startup programming. The IMU output type is I<sup>2</sup>C. Each sensor costs \$35.95 [39].
- LSMDS1 by SparkFun: This linear acceleration sensor can measure accelerations up to 16 g's, and angular velocities up to 2000 degrees/second. The sensor requires a circuit board microcontroller for use, with additional data storage and power components added to it. Additionally, bootloader code needs to be applied to the microcontroller for full functionality. The sensor output type is I<sup>2</sup>C. Each sensor costs \$15.95 [40].
- MPU-9250 by SparkFun: Similar to the LSMDS1, the MPU-9250 is a linear acceleration sensor. The sensor can measure accelerations up to 16 g's, and angular velocities up to 2000 degrees/second. The sensor requires a circuit board microcontroller for use, with additional data storage and power components added to it. Additionally, bootloader code needs to be applied to the microcontroller for full functionality. The sensor output can either be I<sup>2</sup>C, or digital. Each sensor costs \$14.95 [41].

## 4.5: Design Calculations and Modeling

The main metrics to be calculated in the data analysis portion of the system were chosen to be joint forces and torques, which require the measurement of linear and angular acceleration. To develop the equations of motion for the elbow and shoulder, models were created to visualize the metrics to be calculated. The models used are free body diagrams (FBD) of specific segments to display the forces and moments acting on the body at a time. Figure 4 displays the model that will be used in the sensor placement and configuration for testing.



*Figure 4. Diagram displaying the location of the two sensors on the body.*

Figure 5 shows the free body diagram of how the two localized vectors will be created from the global coordinate system using the Polhemus EMT system. Figure 6 shows the free body diagram of the local coordinate system for each of the two sensors used for the Razor sensors. This projected elbow position and movement would then be used in the calculations of the elbow joint metrics.

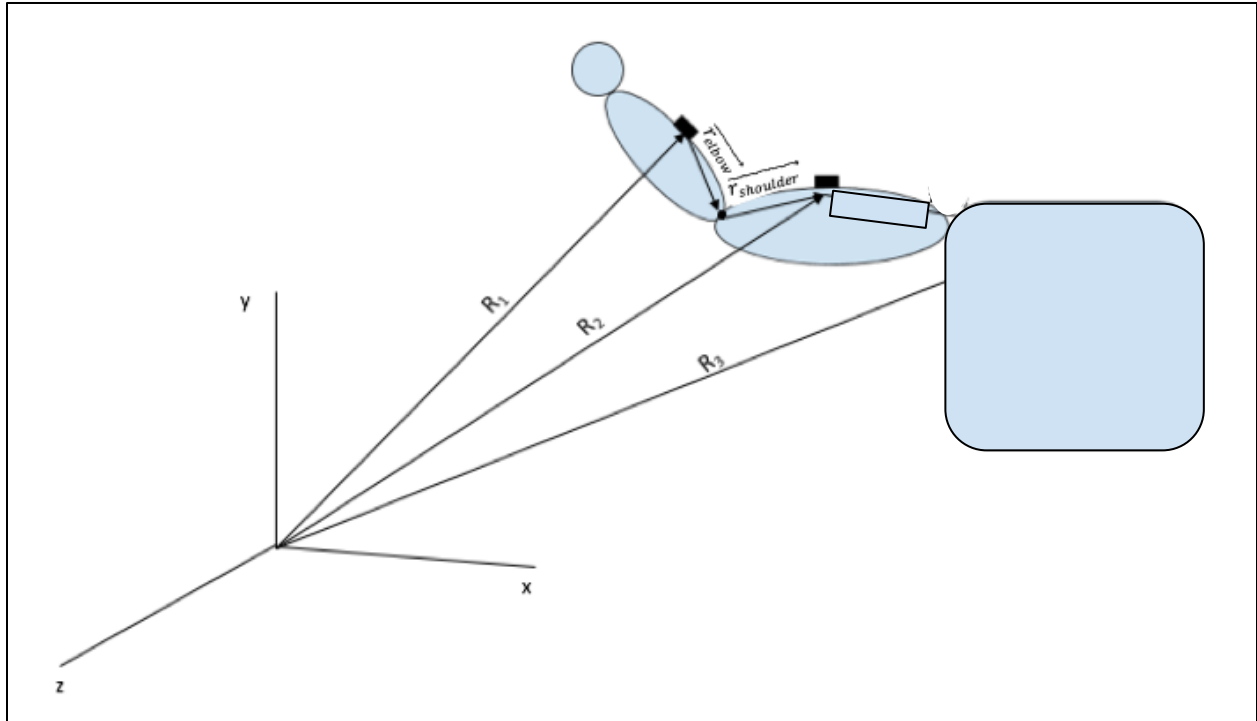


Figure 5. Diagram displaying the local coordinate vectors created from the global coordinate system on the Polhemus EMT System.

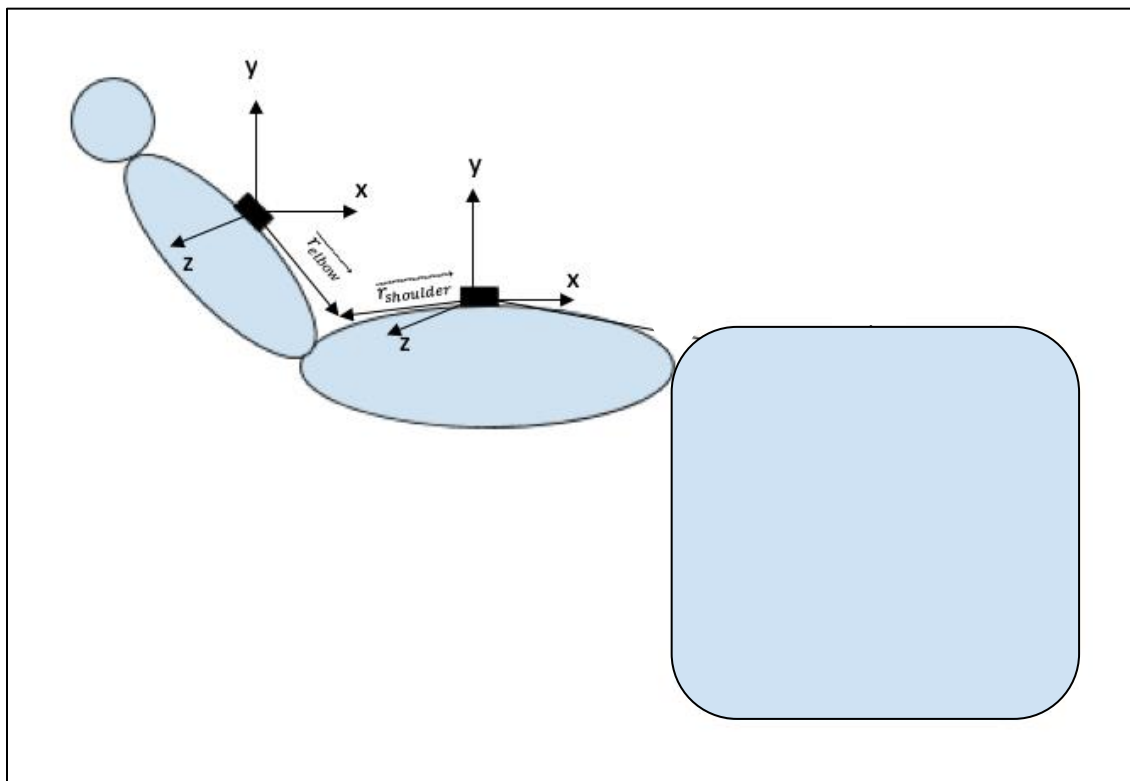


Figure 6. Diagram displaying the local coordinate system and vectors on the Razor Sensors.

Figure 7 displays the FBD of the lower arm segment and the values that will be taken into account to calculate the force and torque experienced at the elbow. The force equation for this model can be seen in Equation 1. All variable definitions for Equation 1 can be found in Equations 2-5 in Appendix A.

$$-\vec{F}_{elbow} + m_{forearm} * \vec{g} = m_{forearm} * \vec{a}_{forearm}$$

Eq 1: The lower arm segment force experienced at the elbow.

Equation 6 shows the elbow torque calculation from the lower arm segment referenced in Figure 7. All variable definitions for Equation 6 can be found in Equations 7-10 in Appendix A.

$$I * \alpha = -\tau_{elbow} + (\vec{r}_{elbow} \times \vec{F}_{elbow})$$

Eq 6: The lower arm segment torque experienced at the elbow.

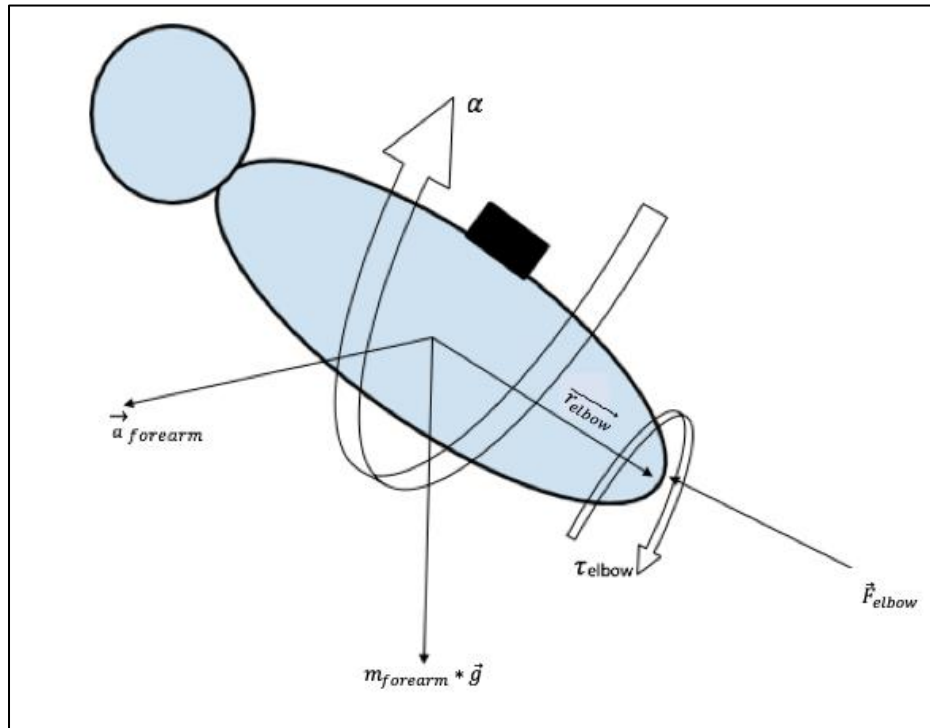


Figure 7. FBD of the forearm segment.

Figure 8 depicts the upper arm and shoulder segment and the values that will be taken into account to calculate the force and torque experienced at the elbow. The shoulder force equation for this model in Equation 11. All variable definitions for Equation 11 can be found in Equations 3,5, and 12-13 in Appendix A.

$$\vec{F}_{\text{shoulder}} + \vec{F}_{\text{elbow}} + m_{\text{upper arm}} * \vec{g} = m_{\text{upper arm}} * \vec{a}_{\text{upper arm}}$$

Eq 11: The upper arm segment force experienced at the shoulder.

Equation 14 shows the shoulder torque calculation referenced in Figure 8. All variable definitions for Equation 14 can be found in Equations 8-10, and 15-16 in Appendix A.

$$I * \alpha = \tau_{\text{shoulder}} + \tau_{\text{elbow}} + (\vec{r}_{\text{shoulder}} \times \vec{F}_{\text{shoulder}}) + (\vec{r}_{\text{elbow}} \times \vec{F}_{\text{elbow}})$$

Eq 14: The upper arm segment torque experienced at the shoulder.

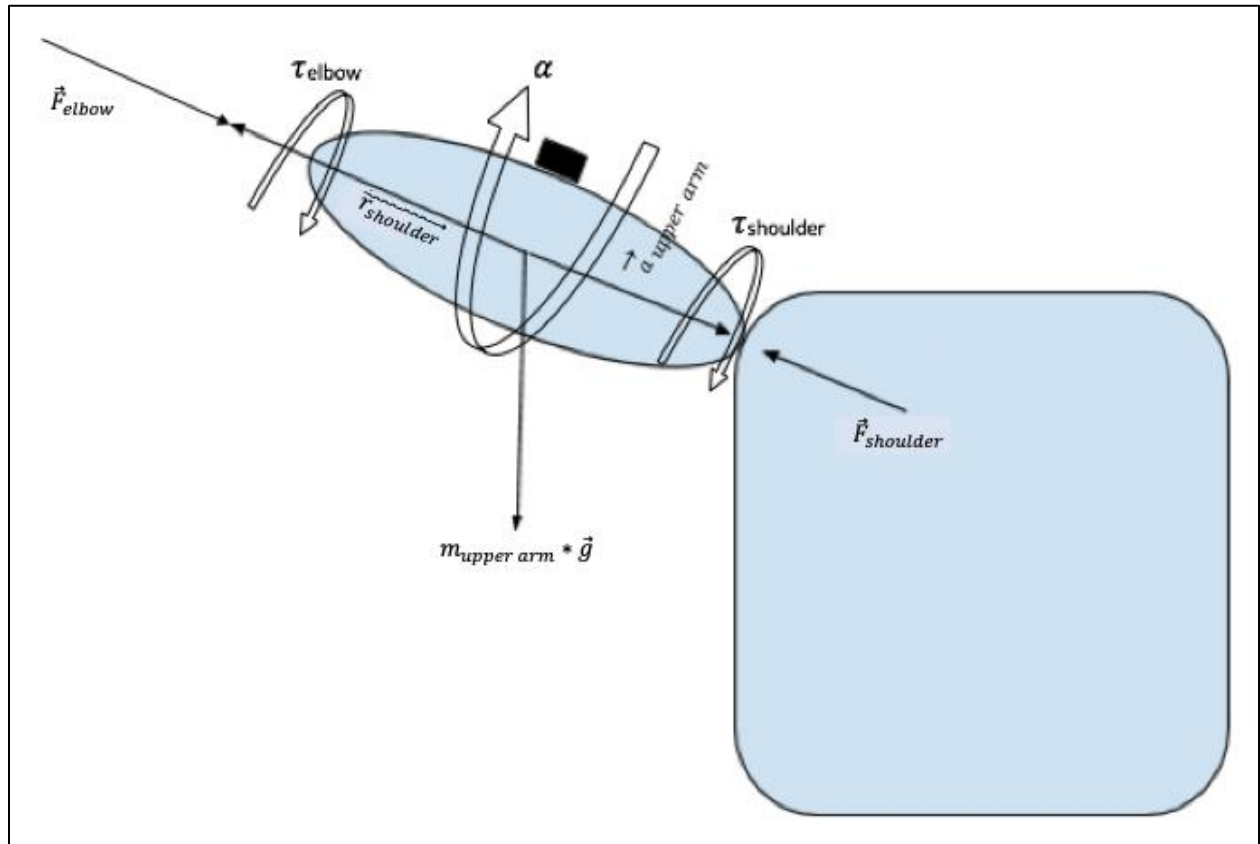


Figure 8. FBD of the upper arm segment.

These equations were used to create a MATLAB script to analyze the raw test data and calculate the desired values as outputs for further statistical analysis.

## 4.6: Feasibility Study and Experiments

Prior to testing the initial system design on subjects, the experiment was preliminarily tested using team members and the gold standard system. To verify the project concept, the Polhemus G4 Electromagnetic Tracking System was used and the team followed the same steps that would be carried out using the designed system in later tests. The testing was conducted by setting up and starting the Polhemus device and placing the sensors in the testing locations as outlined in Appendix D, with the addition of a third sensor at the medial epicondyle. Once the system was assembled and the sensors were placed, a team member was instructed perform simple and controlled movements which could act as conceptual validation for the software and code analysis. The movements included flexing the elbow from 180° to 90° and extending the arm from 90° to 180°. These two motions were carried out using different sensor orientations. By knowing the motions performed, the data could then be analyzed and the results could be reviewed to ensure they are valid for future testing. In addition to angle movements, angle calculations were checked by placing a fourth sensor at the elbow location to determine if the values and positions calculated to represent the elbow were accurate.

By performing these initial experiments, the team did not only determine that the software and code were functioning properly, but also gained confidence in performing these experiments and eliminated any issues or errors as possible for future tests with other subjects.

## 4.7: Final Design Decisions

The basis for the final design of the sensor system was first outlined through research into the field of motion capture and baseball mechanics. Requirements were generated for both hardware and software components of the system, and these were used to filter through potential design candidates. The finalized components of the sensor system were then used to generate a final conceptual design.

### 4.7.1: Motion Sensor Selection

The motion sensor was selected by the team through discussions weighing the advantages and disadvantages of each potential candidate in relation to the needs outlined for the project, and the requirements generated for the hardware. Ultimately, the 9DoF Razor IMU by SparkFun

was selected. The functionality of the Razor made it the most attractive option for the project, as it can capture motion at the required ranges for baseball pitching, and can easily be made wearable. This IMU can store motion data locally to a micro SD card that can then be transferred over to a computer for further analysis. The Razor can also be attached to a small lithium-ion battery for hours of continuous data capture, without the need of long wires that could potentially impede motion. The price of the Razor fits the budget of the project, even with the additional purchases of lithium-ion battery packs and micro SD cards.

#### 4.7.2: Final Conceptual Design

After the components for the wearable sensor system were selected, a final conceptual design was outlined. Each sensor unit would be comprised of one 9DoF Razor IMU, with a micro SD card onboard and a lithium-ion battery for power. One sensor unit would be attached at the approximate center of mass of the upper arm, as well as at the approximate center of mass of the forearm of the pitching arm of the user. The sensors record the linear accelerations and angular velocities of the arm segments during the baseball pitch. This data would be stored locally on the micro SD cards in the sensors in a .csv file, which would then be uploaded onto a computer for analysis. The software designed for the project was written in MATLAB. First, the angular acceleration was derived from the raw angular velocity data. Then using the equations of motion outlined in section 4.5, the forces and torques at the elbow and shoulder were calculated in the MATLAB scripts. These calculated metrics were compared through a sliding window analysis to detect variation over time, indicating the level of fatigue of the user. A baseline variation is first established for the user. Following this, the variation within each window was compared to the baseline to develop an injury risk profile.

### 4.8: Optimization

Design aspects that will need to be optimized are: the locations of the sensors, the method of fixing the sensors to the subject, and the method of comparing the pitches to the baseline.

The ideal location of the sensors will be surrounding the joints of interest, rather than being placed at the joint of interest, so as not to disrupt the natural motion. The sensors ability to track 6 degrees of freedom should enable to projection of the elbow location based on the orientation of the sensor. For the sensors on the upper arm and the forearm it will be necessary to

experiment with internal and external placement, as well as distance of the sensor from the elbow and shoulder. The distances from the elbow and shoulder may impact the accuracy relating to segment rotations and the torque at the joint itself.

The final placement of the sensors was based on the assumption that maximum forces and torques are at early release, where the upper arm is horizontal, the elbow is bent 90 degrees and the palm is facing forward. To most easily follow to derived equations of motion we placed the sensors at the center of mass of the forearm and the upper arm, along the long axis of each segment. In this arm orientation the sensors were placed on the front facing surface of each segment. The forearm sensor positive X direction was oriented toward the elbow, and the upper arm sensor positive X direction was oriented toward the shoulder.

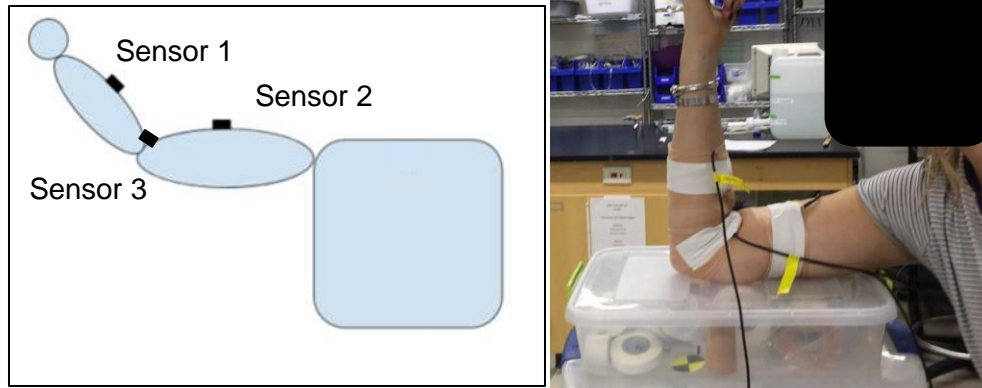
An aspect of the accuracy of the sensor output data is the stability of the sensor with respect to fixation on the subject. If the sensors move independent of the pitcher's arm, the data will become skewed and could result in a false negative or false positive indication of injury risk. Therefore, it will be necessary to develop a method which allows the sensors to remain in place regardless of movement and other factors such as rain or sweat, which may cause motion.

The current proposed method of comparing pitches to the healthy baseline is the use of a sliding window analysis function. This function looks at a given number of pitches at a time and calculates an average and standard deviation for that particular set of pitches. Following the analysis of that window of pitches, the function will conduct the same analysis of the next window of pitches, there can be an overlap of the pitch windows. This overlap can help to filter noise in the data. It will be necessary to optimize the magnitude of the analysis window as well as the overlap between windows in the sliding window analysis. This optimization can be conducted by comparing the results of the program with surveys collected from the pitchers, which record their perceived fatigue.

## 4.9: Preliminary Data

To collect preliminary data a member of the team was outfitted with three Polhemus sensors on the forearm, the upper arm and at the elbow joint. The team member was instructed to keep their arm stable while extending and flexing the elbow in a controlled manner. This preliminary test would provide raw data with expected values for the output, as the degrees of freedom in the motion are limited. The setup of this test is shown in Figure 9 below.

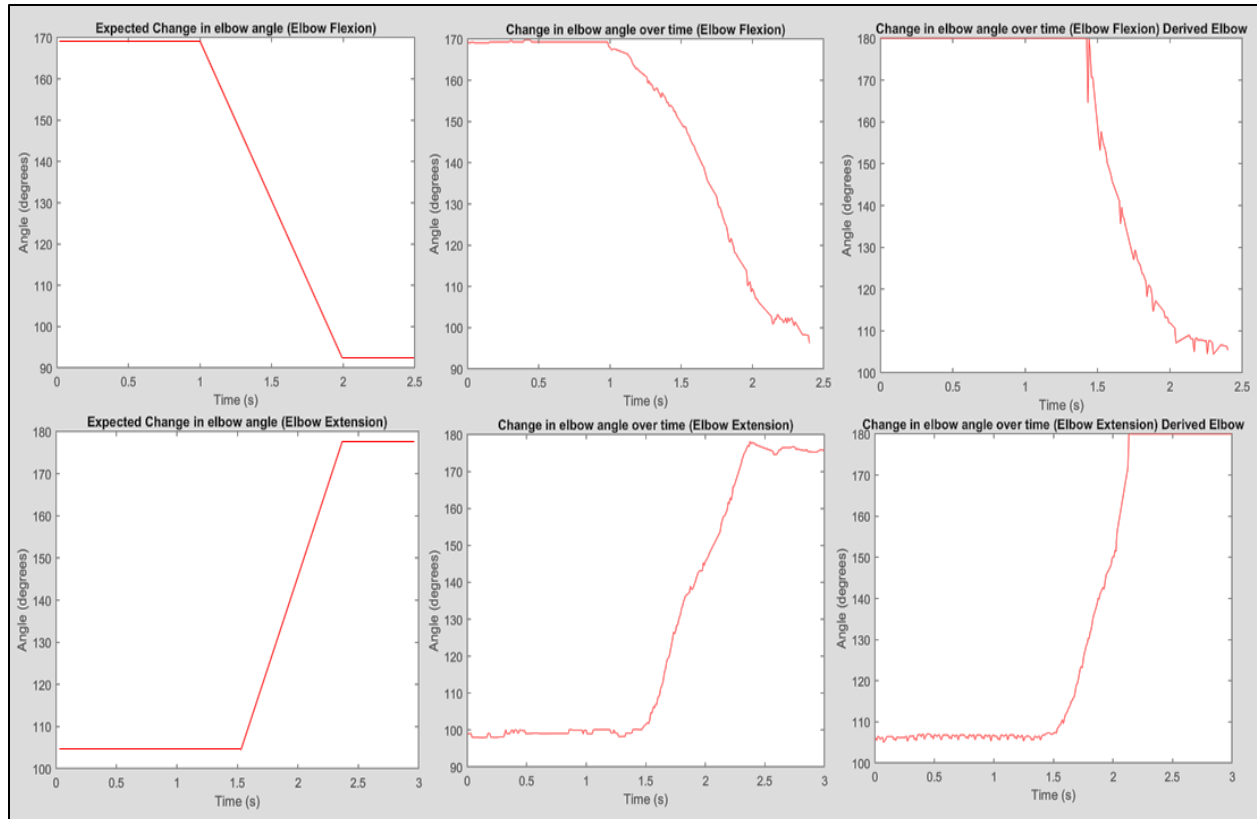




*Figure 9. Preliminary data collection setup using the Polhemus EMT system.*

In addition to the three sensor data based calculations, a function was drafted to derive a theoretical projected location of the elbow based on the orientation and location in space of the sensor. This projected elbow location was derived from both the forearm and upper arm sensor locations and orientations. Using MATLAB code the graphs shown in Figure 10 were generated to show the actual and projected angle change of the elbow.

Angular velocity and angular acceleration were calculated using the equations of motion outlined in section 4.5. These graphs were developed using the raw data from all three of the sensors.



*Figure 10. Expected change in elbow angle (left), Actual change in elbow angle (center), Derived change in elbow angle from projection (right).*

The actual elbow angle change and derived elbow angle change are comparable to the expected elbow angle change, showing that we are able to accurately measure the motion, and evaluate the motion using the limitations of a two-sensor definition of the joint.

# Chapter 5: Final Design Verification

## 5.1: Hardware Design Requirements

To ensure that the sensors selected for the motion tracking system were sufficient, we outlined and conducted verification tests for each components. For each requirement, we assigned a test level and strategy to create testing conditions and criteria. There are two different hardware test levels:

- **Usability testing:** includes experiments that help create an understanding of the target user experience of a product.
- **Key component testing:** includes experiments that analyze the functionality of vital sub-systems in a product.

The requirements and verification criteria for the hardware used in the sensor system are detailed in Table 5.

*Table 5. Sensor Subsystem Requirements and Verification Criteria.*

Requirement #	Requirement	Test Level	Strategy	Testing Conditions	Test Criteria
R001	The motion sensors shall record accelerations up to +/- 16 G's	Unit	Key Component Testing	Each motion sensor shall be moved in free space during a baseball pitch while recording motion coordinate and time values, and transmit these values to the data collection interface	Pass/Fail: sensor must record motion up to 16 G's
R002	The motion sensors shall record motion up to an angular rate of 2000 degrees per second.	Unit	Key Component Testing	Each motion sensor shall be moved in free space during a baseball pitch while recording motion coordinate and time values, and transmit these values to the	Pass/Fail: sensor must record motion up to 2000 deg/s

				data collection interface	
R003	The motion sensors shall record motion in six degrees of freedom; three translational and three orientational axes.	Unit	Key Component Testing	Each motion sensor shall be moved in free space during a baseball pitch while recording motion coordinate and time values, and transmit these values to the data collection interface	Pass/Fail: sensor must report out motion in six degrees of freedom in relation to the global coordinate system (+/- x, y, z, azimuth, elevation, roll)
R004	The motion sensors shall have a sampling frequency of at least 120 Hz.	Unit	Key Component Testing	Each motion sensor shall be moved in free space during a baseball pitch while recording motion coordinate and time values, and transmit these values to the data collection interface	Pass/Fail: sensor must report out motion coordinates at a rate of at least 120 samples per second.
R005	The sensor system shall operate for a minimum of four hours straight.	System	Key Component Testing	The sensor system shall record motion coordinates and time values during baseball pitches over a four hour time span, and transmit these values to the data collection interface	Pass/Fail: the sensor system must be able to continuously record data for four hours
R006	The system of motion sensors shall weigh less than one pound.	System	Usability Testing	The motion sensors that are worn by the user during motion capture will be weighed	Pass/Fail: the total weight of the wearable components in the system must be less than one pound

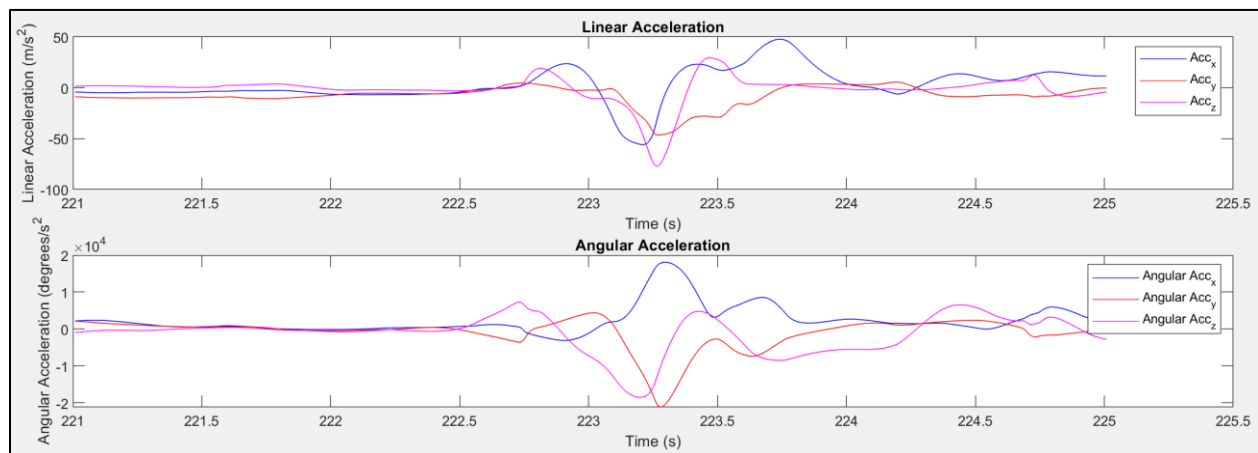
R007	The motion sensors shall securely mount onto the body of the user.	Unit	Usability Testing	A user will be required to apply the motion sensors to their body in indicated landmarks and use the system during a baseball pitch	Pass/Fail: the user must be able to mount the sensors to their body in a secure fashion that prevents disruption of the sensor position on the body during pitching
R008	The sensor system shall store motion capture data locally.	System	Key Component Testing	The sensor system shall be moved in free space during a baseball pitch while recording motion coordinate and time values, and then this data will be transferred onto a computer for analysis.	Pass/Fail: the sensor system must have the capability to store data locally to then be transferred onto a computer for analysis.
R009	The sensor system shall report back motion and time coordinate outputs in I <sup>2</sup> C.	Unit/System	Key Component Testing	The sensor system shall be moved in free space during a baseball pitch while recording motion coordinate and time values, and transmit these values to the data collection interface	Pass/Fail: the outputs of the sensor system to the data collection interface must be in I <sup>2</sup> C.
R010	The motion and time coordinates of the sensor system shall interface with the data collection interface	System	Key Component Testing	The sensor system shall be moved in free space during a baseball pitch while recording motion coordinate and time values, and transmit these values to the data collection	Pass/Fail: the motion coordinates and time value outputs from the sensor system must be transferable and able to

	written in MATLAB code for analysis.			interface	manipulate with the MATLAB code written to interpret the data
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## 5.2: Hardware Verification Testing

To test the 9DoF Razor IMU M0, referred to as the Razor or sensor, we conducted a series of experiments which would assess the ability of the IMU to meet the prescribed requirements in the table above.

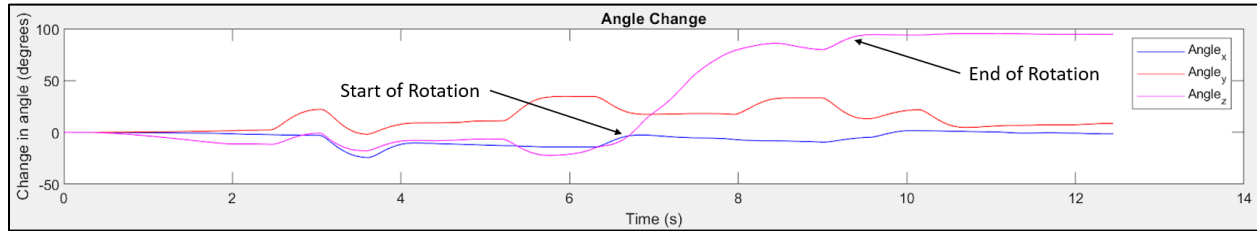
- *R001, R002*: To ensure that the Razor could measure linear accelerations and angular velocities up to the specified ranges of the first two requirements, we placed the Razors' on a subject a recorded the motion of an isolated baseball pitch. The data from this test, shown in Figure 11, supports the Razor's functionality to meet these requirements.



*Figure 11. Raw accelerometer and gyroscope data during a single baseball pitch.*

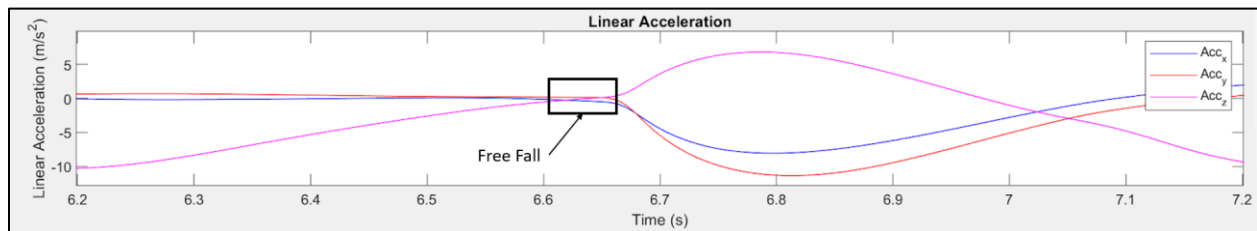
- *R003, R009, R010*: In order to test the rotational measurement component (gyroscope), the 9DoF Razor IMU M0 was placed on flat on a benchtop, turned on, and then rotated 90 degrees counterclockwise, around the z, y and x axes -- wherein each axis rotation was collected as a separate trial and data file. The raw data was compiled to an excel file and filtered using a second order Butterworth filter in MATLAB. We processed the filtered data using MATLAB scripts which would calculate the linear acceleration, the change in

angle and the angular acceleration. The change in angle is shown below for a 90-degree rotation about the z-axis in Figure 12. This visualization is derived using the raw data from the gyroscope.



*Figure 12. Change in angle using the raw gyroscope data from Razor validation test 90-degree rotation about the Z axis.*

In addition to the rotation trials we conducted a drop test, in which the unit was dropped from 12 inches above a soft surface. When the Razor is still on the table with the z-axis in vertical orientation the acceleration in the z direction is equal to gravity. When in free fall, with the same orientation of the Razor, the acceleration in the z-direction should be cancelled out as the entire unit is accelerating with gravity. This expected outcome is validated in Figure 13, which shows the z acceleration as zero during the period of free fall.



*Figure 13. Linear acceleration during free fall of the Razor, where during the period of free fall, the linear acceleration in the Z direction is cancelled out by gravitational acceleration of the entire unit.*

Overall the 9DoF Razor IMU M0 unit outputs the expected values for the experimental motions. From these tests we validated that the raw data is collected in six degrees of freedom (R003), all of the data collected is related to a relevant local time point (R009), and found that the output data of the 9DoF Razor IMU M0 is compatible with MATLAB analysis (R010).

- *R004*: The lower limit for the sampling rate of the sensors was required to be at least 120 Hz. To test this requirement on our IMU's, we collected motion data with the Razor and calculated the sampling rate from the raw time points in the data. The Razor's logged

motion data once about every seven milliseconds, resulting in a real-world sampling rate of about 142 Hz exceeding R004.

- *R005*: To test the battery capabilities of the Razor setup, the IMU was left on for four hours straight. The Razor had no issues, and collected motion data for the entire period meeting R005.
- *R006*: The system of motion sensor is a unit comprised of the 9DoF Razor IMU M0, a micro SD card, and a lithium-ion battery. The total weight of a single sensor unit is 0.0306 pounds. The maximum number of units that a single subject will wear at any given time is no more than three, placing the maximum weight at 0.0918 pounds. Therefore, R006 is met, as there is no configuration of the system where the weight of the sensors will exceed one pound.
- *R007*: To test the wearability of the Razor's, we mounted the Razors on a subject and marked the location of the sensor units on subjects' arms using pen. The sensor units were secured to the forearm and upper arm at their respective centers of mass. The method of securing the sensor units was holding the sensor unit to the arm, wrapping multiple layers of pre-wrap directly over, above and below the unit, then securing the unit in place using one piece of athletic tape wrapped twice around the arm. Subjects completed 20-55 pitches, and the location of the sensor did not move from its marked location after the completion of the pitches. The sensor unit passes R007, in that it can be secured to a location on a subject.
- *R008*: The sensor writes data to a local micro SD card. Each time the sensor turns on, the sensor writes a new .txt file to the SD card. After turning off the sensor, the SD card inserts to a computer and the data is transferred from the .txt file to a .xlsx file in a standard format. The sensor meets R008.

### 5.3: Software Design Requirements

Following component verification, the software developed for the project was verified. This included verifying the code itself, as well as in conjunction with the sensor components. From the constraints of the software overview, detailed requirements were created. For each requirement, a test level and strategy were assigned to create testing conditions and criteria. There are four different software test levels:



- **Unit Testing:** individual components of the software package are tested for validate that the software performs as intended (i.e. individual functions/scripts with single purposes).
- **Integration Testing:** scripts that have outputs that will later be used together to complete a new function are tested for their compatibility, verifying that the outputs can be integrated together successfully (i.e. the different sets of calculated data work with each other for the next step of calculation).
- **System Testing:** the entire software package is evaluated for final outputs, validating that the code outputs meet the specified requirements (i.e. does the final data output reflect the desired outcome).
- **Acceptance Testing:** the software package and outputs are assessed to confirm that the final product satisfies the user's needs (i.e. does the final data output meet the needs of the user/make sense to the user).

There are two different testing strategies involved with these requirements:

- **White Box Testing:** Low level testing where the tester choses specific cases to input into individual functions/scripts of code. Test cases include legal and illegal inputs for the code. The outcomes for these cases are then compared to the expected outcome, whether it be a specified type of output, or an expected error/failure of a function. Typically used in unit, integration, and system testing.
- **Black Box Testing:** High level testing where the tester tries out various functions of the software from the user-end of the system. The tester does not know the internal structures of the code, and will instead be providing inputs to the software in the form of prompted values or clicks. The outputs from these actions are then compared to the expected outcomes. This testing highlights errors such as incorrect/missing functions, interface errors, and database access errors. Typically used for integration, system, and acceptance testing.

The requirements for the software used in the sensor system are detailed in the following table.

*Table 6. Software Subsystem Requirements and Verification Criteria.*

Requirement #	Requirement	Test Level	Strategy	Testing Conditions	Test Criteria
R011	The software	Unit	White Box	The MATLAB	Pass/Fail: The

	shall receive raw data from the sensor system in the form of a .csv file			function used to open/read the raw motion .csv file is pointed towards a .csv file with expected data columns, a .csv file with insufficient data columns, and a file with incorrect file format	function shall only execute if the file path points towards a .csv file with data points for six degrees of freedom and time points
R012	The software shall create cell arrays of continuous acceleration/angular velocity/time data across all sensors	Unit	White Box	The MATLAB function for sorting the cell arrays of sensor data shall be fed data from the forearm and upper arm sensors and create sorted arrays of the same size	Pass/Fail: The appended arrays must all have the same size between the forearm data matrix and the upper arm data matrix
R013	The software shall calculate the angular acceleration of the arm segments during a baseball pitch	System	Black Box	The motion of the user's arm during a baseball pitch shall be captured using both the sensor system and an external motion capture system	Pass/Fail: The software must calculate the angular acceleration of the arm segments
R014	The software shall calculate the overall force at the elbow during a baseball pitch	System	Black Box	The motion of the user's arm during a baseball pitch shall be captured using both the sensor system	Pass/Fail: The software must calculate the overall force at the elbow
R015	The software shall calculate the overall torque at the elbow during a baseball	System	Black Box	The motion of the user's arm during a baseball pitch shall be captured using both the sensor system	Pass/Fail: The software must calculate the overall torque at the elbow

	pitch				
R016	The software shall indicate to the user when the standard deviation of overall force at the elbow implies a dangerous level of injury risk	System	White Box	The system shall monitor the maximum forces at the elbow during baseball pitches of a healthy/unfatigued player, then monitor the forces at the elbow during baseball pitches of an unhealthy/fatigued player	Pass/Fail: The software must indicate that the standard deviation of overall force in the unfatigued pitcher is at a healthy level, and that the standard deviation of overall force in the dangerously fatigued player is at an unhealthy level
R017	The software shall indicate to the user when the standard deviation of overall torque at the elbow implies a dangerous level of injury risk	System	White Box	The system shall monitor the overall torque at the elbow during baseball pitches of a healthy/unfatigued player, then monitor the varus torques at the elbow during baseball pitches of an unhealthy/fatigued player	Pass/Fail: The software must indicate that the standard deviation of overall torque in the unfatigued pitcher is at a healthy level, and that the standard deviation of overall torque in the dangerously fatigued player is at an unhealthy level
		Acceptance	Black Box	The sensor system shall monitor the	Pass/Fail: The user must

				motion of a user over the course of a pitching practice	review the injury risk outputs and verify that they correspond to their level of fatigue
--	--	--	--	---	--

- *R011*: The code is able to receive the raw data from the sensor in the form of a csv file. Because these sensors write to a .xlsx file format this is the csv format the team elected to use. These lines of code from script datasorting.m (Figure 14) show that the user is prompted to input the .xlsx file names, which the script then stores as a variable. Each variable is passed through the prescribed xlsread MATLAB function.

```
x = input('Forearm data file \n', 's');
y = input('Upper arm data file \n', 's');
tic
%% Forearm Data sort
data_fa=xlsread(x);
```

Figure 14. *datasorting.m* input prompts.

The outcome of the lines of code above result in the following prompts, shown in Figure 15, and user inputs in the command window.

```
Command Window
Forearm data file ←
Subject_1_Date_Feb_15_2019_fa.xlsx←
Upper arm data file ←
fx Subject_1_Date_Feb_15_2019_ua.xlsx|←
```

Figure 15. *datasorting.m* user input in command window.

When the user input is not in a .xlsx file format the following error is given, shown in Figure 16. This ensures that the only files able to be entered into this code are the raw data files. This is a precaution to ensure that an already sorted .mat file cannot be accidentally re-fed and wrongly manipulated by the data sorting script.

```
Command Window
Forearm data file
Subject_Raz_date_ZY_pitch_1.mat
Upper arm data file
Subject_Raz_date_ZY_pitch_1.mat
Error using xlsread (line 257)
File Y:\MATLAB\Subject_Raz_date_ZY_pitch_1.mat not in Microsoft Excel Format.

Error in datasorting (line 12)
fx data_fa=xlsread(x);
```

Figure 16. Error in Command Window due to incorrect input file format.

- *R012*: The output of the data sorting script is a .mat file type which is named to that specific subject and session. In this .mat file all related matrices must be the same size. Figure 17 is a screenshot of the details window of MATLAB, the pairs of data are newdata\_fa/newdata\_ua, f\_elbow\_mag/f\_shoulder\_mag, max\_forces\_elb/max\_forces\_sho. Each pair is the same size and format matrix. This allows the paired matrices to be compared to one another.

Subject_3_date_Feb-08-2019_pitch_1.mat ...		
	Name	Value
	newdata_fa	143585x7 double
	newdata_ua	143585x7 double
	f_elbow_mag	143585x1 double
	f_shoulder_mag	143585x1 double
	max_forces_elb	50x1 double
	max_forces_sho	50x1 double

Figure 17. Details window in MATLAB showing the paired matrices as being the same size as their paired matrix.

- *R013*: This section of code (Figure 18) shows how the team calculates the angular acceleration in degrees per second squared from the filtered IMU output (newdata\_fa(:,4 or 5 or 6) is in the form degrees per second). The variables gyr\_x/y/z represent this calculated angular acceleration.

```
gyr_x = newdata_fa(:,4) / (newdata_fa(2,7)-newdata_fa(3,7));
gyr_y = newdata_fa(:,5) / (newdata_fa(2,7)-newdata_fa(3,7));
gyr_z = newdata_fa(:,6) / (newdata_fa(2,7)-newdata_fa(3,7));
```

Figure 18. Code calculating angular acceleration from raw data output from the IMUs.

The result of this section of code is shown in Figure 19, graphing angular acceleration with respect to time. The sensor was turned in the Z-Y plane, so the sensor accelerated in the X direction. The motion began at approximately four seconds and lasted for one second. As such the angular acceleration peaks between four and five seconds.

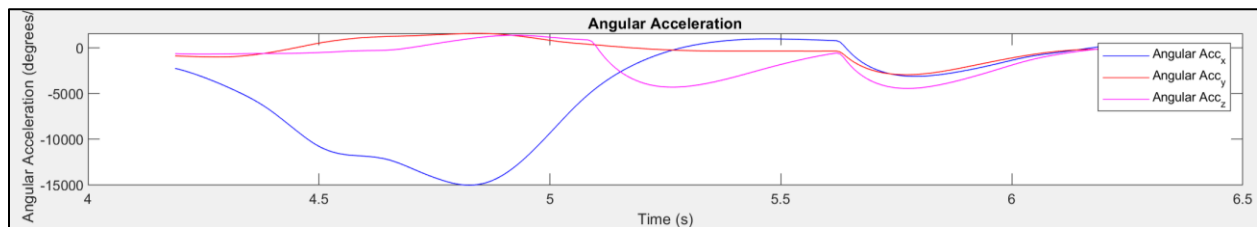
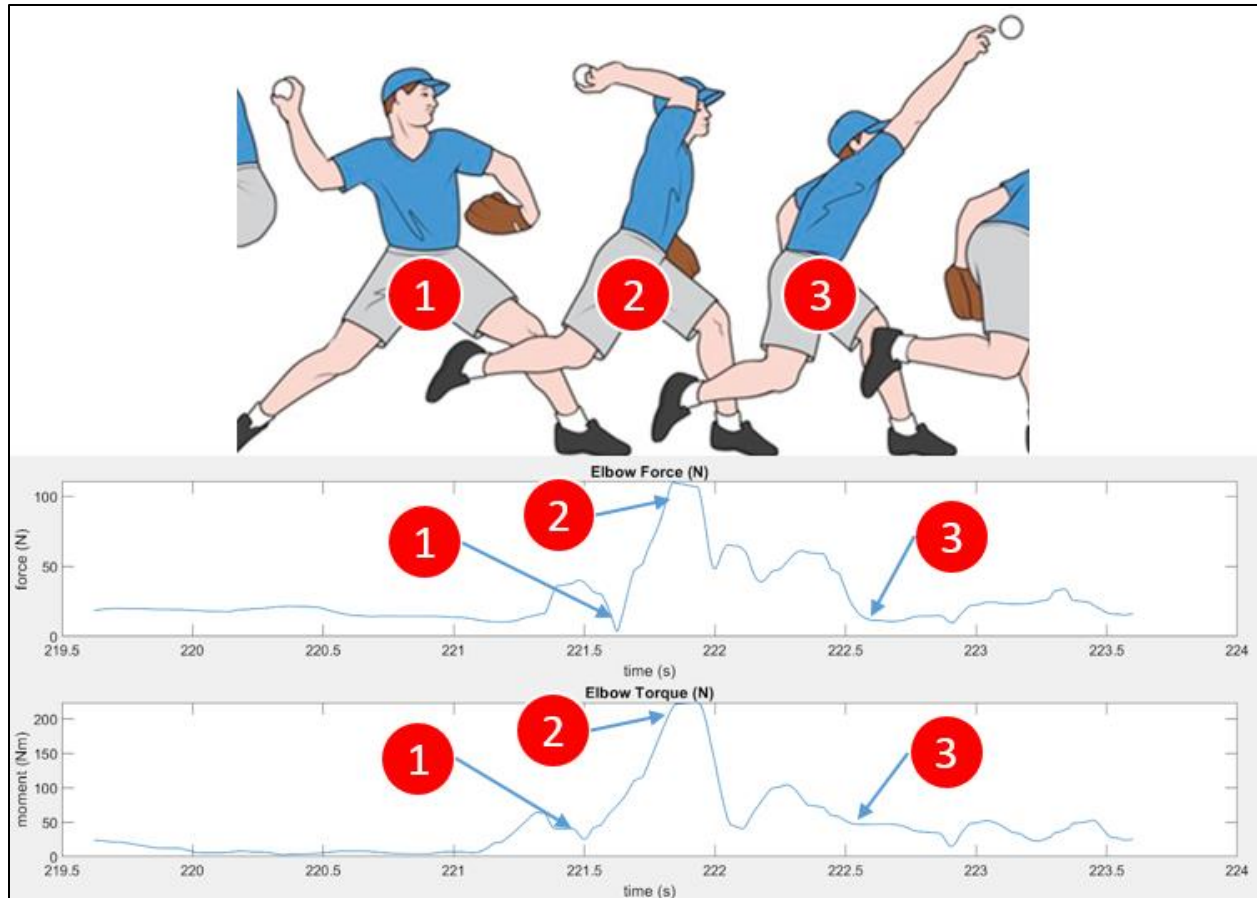


Figure 19. Graphical representation of the angular acceleration over time.

- *R014, R015*: The code is able to calculate the forces and torques of the elbow during the pitch. This is achieved using the equations outlined in Section 4.5. Figure 20 shows an isolated single pitch from Subject 8. These graphs show the force and torque at the elbow throughout the pitch. These values are consistent with the values found from literature in Section 2.4.



*Figure 20. Calculated force and torque at the elbow during an isolated pitch.*

- R016, R017:* The system finds the maximum value of force and torque for each pitch using the same system for each calculated value. These maximum values are then fed into a function which uses the first base pitches (base pitches is set by the user) to calculate an initial healthy standard deviation based on these healthy base pitches. The sensitivity is set to 10% of the healthy standard deviation. The code then calculates the standard deviation of the following pitches in windows the size of the base pitch window, with a step over of half the window (unless the window size is an odd value, in which case the step over is rounded up to the nearest integer). These new experimental standard deviations are compared to the value of the healthy standard deviation plus the 10% sensitivity. If the experimental standard deviation is greater than the sum of the healthy standard deviation and the sensitivity the window is flagged, shown by the boxes in Figure 21.

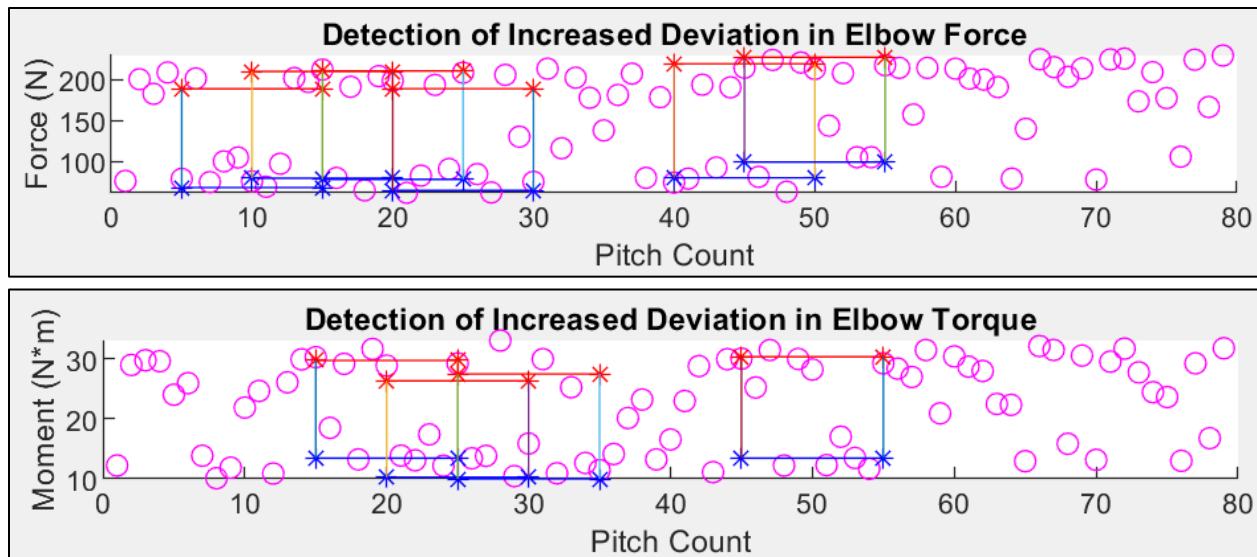


Figure 21. Detection of increased deviation in elbow force (top) and elbow torque (bottom). Windows of pitches with increased deviation are indicated by the boxes.

In addition to the graphical output the user is shown the messages in Figure 22, warning that the deviation of the experimental window has increased to a potentially injurious degree in comparison to the healthy baseline standard deviation.

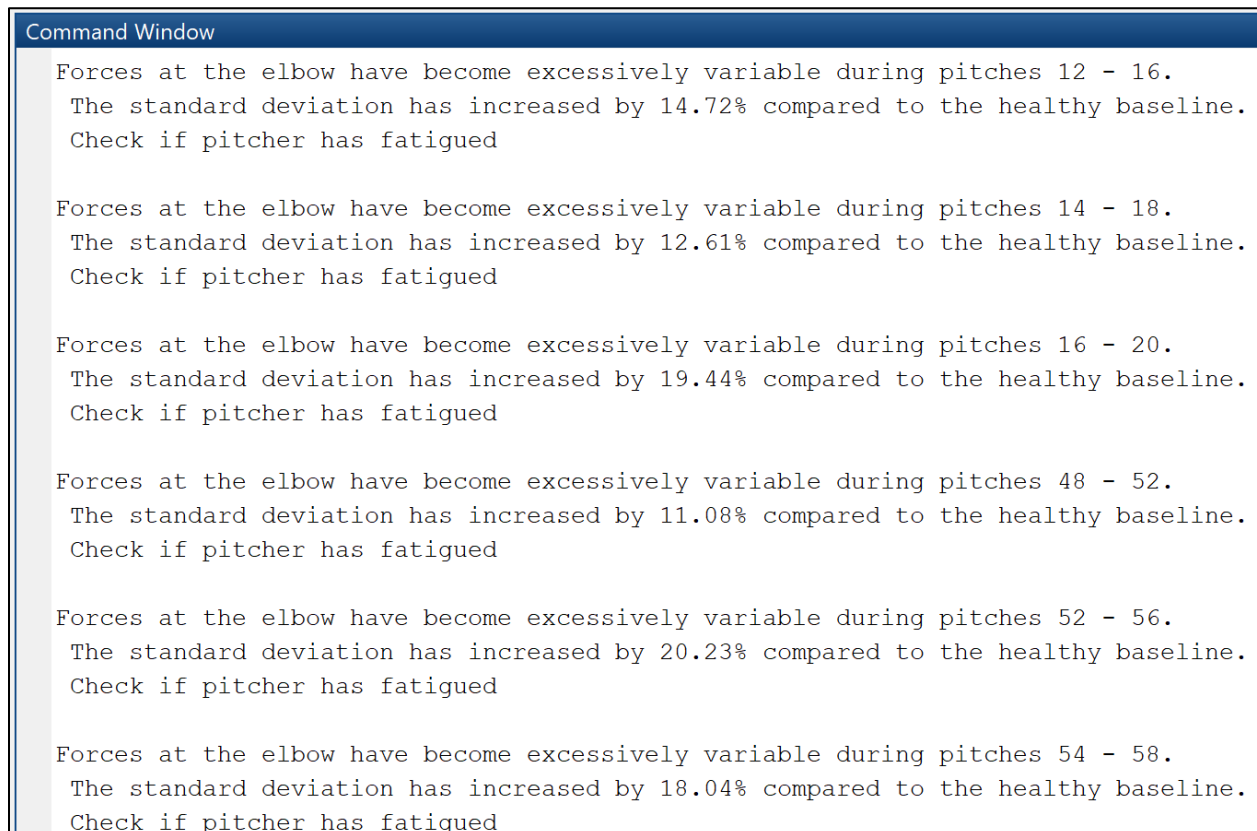


Figure 22. The resultant command window, displaying the warning message that the standard deviation of the pitches has increased to a potentially injurious degree.

## 5.4: Preliminary Subject Testing

We conducted preliminary subject testing with members of the team. The sensors were mounted in the same manner the team planned to conduct the live tests - using pre-wrap and athletic tape. We used these tests to experiment with the location and orientation of the sensors on the arm. We found that mounting the sensors was most repeatable by the subject holding their arm out in front of them, angled out slightly to the side, and with their palm up. This allowed us to measure the forearm and upper arm, as well as the circumference of the bicep. From these measurements a pen mark could be made at the center of mass over the biceps brachii on the internal of the upper arm and over the brachioradialis on the forearm. Simple and controlled motions were completed such as elbow flexion and extension, forward rotation of the forearm in a 90-degree angle of a horizontal forearm, and adduction of the upper arm held at horizontal with the forearm raised at a 90-degree angle. These tests provided understanding of how the sensors operated and how to conduct a test in such a way that the data from the temporally local sensors would be comparable within the system.



# Chapter 6: Design Verification- Discussion

## 6.1: Methodology Summary

We began our project by conducting initial research to better understand the problem statement and to find the best method for a solution. This initial research included gaining understanding of the anatomy of the elbow and shoulder, the phases of a baseball pitch, and the biomechanics of a baseball pitch as well as the effects on the elbow joint. This research allowed us to understand the causes behind elbow injuries, not only at an anatomical level, but also specifically due to the mechanics of a baseball pitching motion.

Following our initial literature review, our team moved into the design stage of our project. This stage was twofold, as we needed to design both the hardware and the software subsystems for motion detection and analysis of the biomechanics, respectively. First, we created design requirements for our potential IMU using metric ranges from our literature review. After reviewing these requirements, a list of diverse IMU's was compiled for comparison. Ultimately, the 9DoF Razor IMU M0 was selected for the project. We created a data analysis system using MATLAB software. This code included equations of motion that would calculate forces and torques from our raw motion data. These calculations were then analyzed further to find unhealthy deviation in the joint forces and torques that could lead to injury.

Preliminary verification testing was done to ensure all processes and systems were set up correctly. Preliminary tests were executed first with the Polhemus EMT System on a group member to collect sample data. The tests were done using known motions that would have known results to verify the code calculations. This data was then executed by the MATLAB code to ensure all equations worked properly.

We then began collecting data from the WPI baseball pitchers. Human subject testing was completed with approval from the WPI Institutional Review Board with informed consent from all human subjects. The subjects began their participation by completing a subject intake survey to collect information such as history of injury and baseball experience, and a pre-pitching fatigue assessment survey. At the conclusion of the pitching session, a post-pitching fatigue assessment survey was also administered. The WPI baseball pitchers participated in the baseline data collection protocol. This entailed connecting the Razor sensors to a pitcher at the

beginning of practice and collecting continuous data throughout the session. Fatigue data was also collected during a pitching session on two former Becker College baseball players. This fatigue protocol was similar to the baseline data collection sets, except the subject was asked to perform an exercise to induce a greater amount of fatigue in the arm between throwing sets.

With the data collected from the preliminary tests as well as at each pitching session, we were able to analyze results using our MATLAB code. The MATLAB code ran the input of raw data, executed the functions and created an output of joint forces and torques experienced during each pitch. From these calculations, further analysis was conducted to determine the percent deviation from the baseline data to predict risk of injury.

## 6.2: Summary of Data Collection and Analysis

As mentioned in Chapter 5.2, we verified the Razor sensors prior to field data collection to ensure all parameters were correct. The tests for verification included joint angle tests, a drop test, plane turning, and known motions. The joint angle tests entailed performing flexion and extension motions. These motions were known to go from  $180^\circ$  to  $90^\circ$  for flexion or  $90^\circ$  to  $180^\circ$  for extension. The drop test was performed to ensure that the Razor sensor was reading acceleration correctly. The planar rotation test consisted of laying a Razor sensor flat and turning it  $90^\circ$  about one axis as a time. This test allowed us to see that the sensor was collecting in the correct orientation and that the angular accelerations as well as angles were reading accordingly. The final verification test performed was collecting data from known motions. These known motions included starting the arm at an upright  $90^\circ$  position and turning the arm downward, which allowed us to verify that there would be an elbow moment experienced from our calculations. The other motion was moving the arm from the initial upright  $90^\circ$  position and using the shoulder to turn the arm toward medially. This motion would be verified to not produce an elbow joint moment from our calculations.

The system verification allowed us to begin data collection with the subjects. This data was then executed through our MATLAB code to calculate the joint metrics of interest. Once the calculations were complete, the system would further analyze these calculations statistically to determine when a risk of fatigue was present.

### 6.2.1: Human Subject Testing

The aim of our human subject testing was to collect data for healthy and fatigued pitching -- natural or induced -- to test the system and its ability to identify fatigue. More specifically, the goals of our human subject testing were to:

1. Gather field data from pitching practices to test the abilities of our code,
2. Use the system in real-world operating conditions to analyze any hardware limitations,
3. Test the feasibility of the system's operation protocol,
4. Conduct usability testing to assess the practicality of the physical system.

We received approval from the university IRB to conduct human subject testing with adults prior to the start of the study (Appendix B). Subject testing was done by collecting data from pitchers of the WPI Baseball Team and two former Becker College baseball pitchers. All testing was done in the WPI Sports & Recreation Center. Three types of data collection sessions occurred: baseline data collection, induced arm fatigue data collection, and usability testing.

#### *Baseline Data Collection*

To address the first three goals for our human subject testing, the team conducted baseline data collection sessions. We began data collection by reading a consent form to our perspective subject followed by collecting basic information outlined in our Subject Intake Survey, which can be found in Appendix C. This data was then recorded into the Qualtrics program for organization. The baseline data collection was performed by placing two sensors on the arm of a subject, one at the center of mass of the upper arm and one at the center of mass of the lower arm, and allowing them to collect data through an entire practice. The data was monitored by starting a timer when the sensors were turned on, lapping the timers at the beginning of each new pitch, and ending the timer when the sensors were removed and turned off. A detailed outline of the data collection process can be found in the Baseline Data Collection: Field SOP in Appendix D. Once the pitching session was complete, the subject was asked to complete a Subject Survey: Post Session, which can be found in Appendix E, to rank their levels of fatigue and pain. This data was also recorded into the Qualtrics program for organization and review. A total of 8 subjects participated in the study, and 9 data sets were

collected for the baseline data collection. All subjects were members of the WPI Baseball team, between the ages of 20 to 22 years old.

### *Induced Arm Fatigue Data Collection*

In addition to the baseline data collection sessions, we also collected data using an induced arm fatigue protocol to continue to address the first three of our goals for human subject testing. The purpose of these sessions was to induce fatigue in the pitching arm, so the team would have data that could reliably be considered as “fatigued.” Two male subjects participated in this portion of the study, and two data sets were collected. These subjects were former Becker College baseball pitchers, ages 25 and 27 years old. This arm fatigue session included the same process as the baseline data collection sessions, but in between pitching sets the subjects were asked to perform arm cycle exercises to further fatigue the arm muscles. The induced arm fatigue protocol can be found in Appendix F.

### *Usability Testing*

To address the usability of our system, our last goal for human subject testing, our team experimented with the manner in which the sensors were attached to the subjects. At first, pre-wrap was wrapped fully around the sensor and the subjects arm, and secured with a piece of athletic tape over the sensor. However, based upon feedback from the subjects, the sensors did not feel secured in place and on occasion slipped out. To address this, we opted to wrap the sensors and arm fully with multiple layers of pre-wrap, and then fully encircle this with athletic tape. This kept the sensors securely in place, but there were issues with the tape being too constrictive when the subjects went to begin pitching. To fix this issue, the subject was asked to flex their arm while the athletic tape was wrapped to account for the extra motion of the bicep muscle during the pitch. This approach, shown below in Figure 23, was received positively by the subjects, and the sensors securely stayed in place on both segments of the arm during a full pitching practice without restraining any range of motion. One downside to the sensor system in its prototype state was that the subject would have difficulty in attaching the sensors to themselves, and would require the assistance of another person.



*Figure 23. Subject wearing the sensor system during a pitching session.*

### 6.2.2: Data Collection Results

The participation in the study included nine pitchers from the WPI Baseball Team (male, ages 20-22) and two former Division 1 pitchers from Becker College (male, ages 25-27). Two of the sessions had technical difficulties which resulted in incomplete data sets and were not included in the results for analysis. Additionally, one subject reported a recent elbow injury in his intake survey and thus his session data was not included in the results for analysis either. From these subjects we were able to collect data from 9 independent pitching sessions. Each pitcher completed pre- and post-session surveys to allow us to categorize their session in one of three groups: no fatigue ( $n = 4$ ), natural fatigue ( $n = 3$ ), induced fatigue ( $n = 2$ ). An average of approximately 50 pitches was completed during the course of any given session, performed in sets of 20-30 pitches. The exact pitch counts and fatigue classifications for each subject session are detailed in Table 7 below.

*Table 7. Human Subject Testing Pitch Counts and Classification.*

Subject #	Session #	Total Pitch Sets	Total Pitch Count	Fatigue Type
1	1	2	56	Natural
1	2	3	101	None
2	--	--	--	--
3	1	2	50	None
4	1	2	53	None
5	1	2	51	Natural
6	1	2	56	Natural
7	1	2	47	None
8	1	2	43	None
9	--	--	--	--
10	1	2	23	Induced
11	1	4	80	Induced

### 6.2.3: Data Analysis

To analyze the results from the pitching sessions the raw data from the IMUs are converted to a .xlsx format and fed through five MATLAB scripts (Appendices G-K). Prior to MATLAB analysis the team truncates the beginning and end of the .xlsx files such that the first data point from the forearm IMU and the upper arm IMU are the same and close in time to the start of the pitching session, and at the end so that the number of data points are the same, and by extension the matrices in MatLab will be the same size and the rows will be comparable.

The raw data from the IMUs is output in linear acceleration in units of gravity and angular velocity in units of degrees per second. The function datasorting.m (Appendix G) filters the data using a second order Butterworth filter and stores these filter matrices from the upper arm and forearm files into a new .mat format file that is titled according to the subject number,

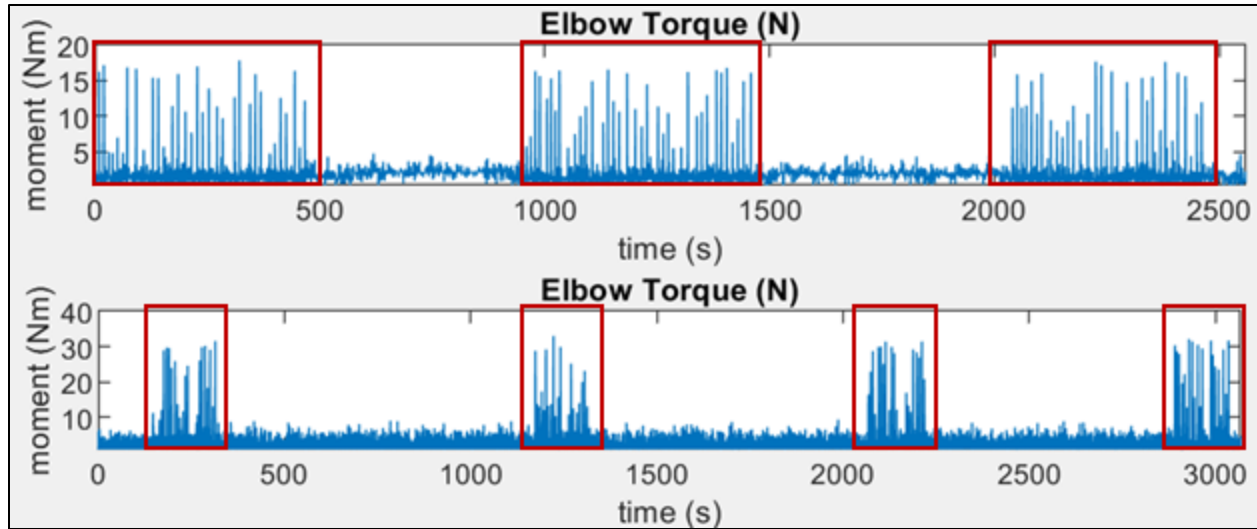
the session date and the session number with that subject. All future scripts append to this session specific .mat file.

After being created the session and subject specific .mat file is fed to the MATLAB script EquationsRigidBody.m (Appendix H). This script uses the equations from Section 4.5 and the data matrices to calculate the forces and torques at the joints of interest. Due to the limitations of the sensors (orientation of the sensor is locally independent) the team has simplified the calculation process by assuming that the arm is in the standard release position (90 degrees) at all points of the pitch, shown by Figure 24 below.



*Figure 24. Video motion capture data demonstrating the standard assumed position of the pitching arm during the late cocking and acceleration phases of the pitch.*

This assumption allows for quicker analysis, but should still provide maximum values of the pitch at consistent checkpoints of the motion. This assumption also affects pitchers with variable form from the form in literature. Because the basis of the system relies on in-subject variance, it is only necessary that for all pitches by a subject the assumptions and calculations remain consistent.



*Figure 25. The output of EquationsRigidBody.mat for a non-fatigued subject performing 101 pitches (top) and an induced fatigue subject performing 80 pitches (bottom), where the sets of pitches are indicated in red boxes.*

Based on the calculations of force and torque at the elbow, MaxForces.mat (Appendix I) sorts the data into time windows provided by time points measured by observation during the pitches. Between every two time points exists a window of time during which a single pitch has occurred. As a result, the code can determine the maximum force and torque at each joint of interest within each individual pitch. These values are sorted into individual arrays in which the index of the value in the array is the pitch count of that individual pitch within the session.



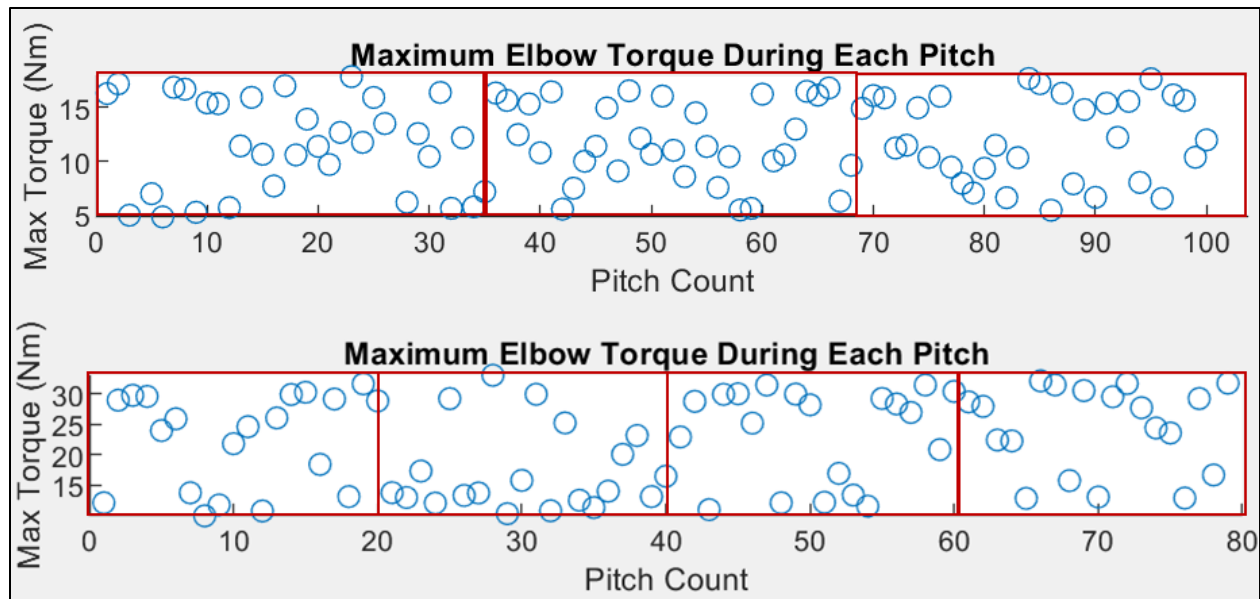


Figure 26. The output of MaxForces.mat for a non-fatigued subject performing 101 pitches (top) and an induced fatigue subject performing 80 pitches (bottom), where the sets of pitches are indicated in red boxes.

These arrays are fed into StatAnalysis.mat (Appendix J) and SensitivityTesting.mat (Appendix K) which creates a baseline window and then reviews the subsequent pitches in small test windows to identify unhealthy variation. The width of the baseline dependent on the when the max values in the session reach a steady state, as determined through a cumulative average. The test windows are then slid across the pitch count, with an overlap half the width of the test window, as shown in the session example below. In this example the baseline width is 10 pitches, the test window is a width of 6, resulting in an overlap of 3 pitches between the windows.

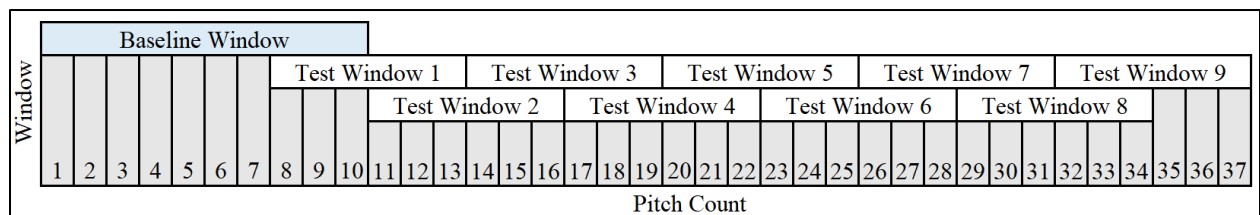
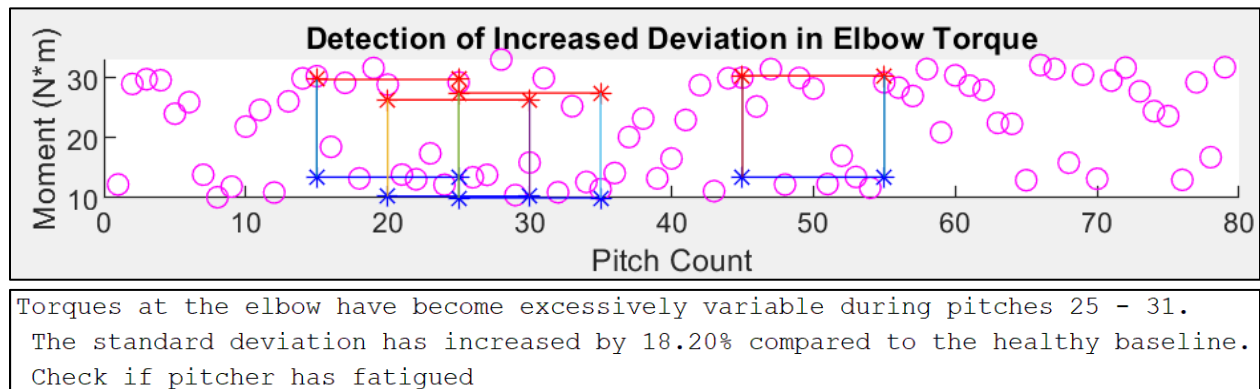


Figure 27. Example of sliding window analysis.

From the baseline window a healthy standard deviation is established. A percent increase on the healthy standard deviation is calculated and added to the healthy standard deviation in order to set an acceptable deviation range. If the test window's standard deviation is greater than

the acceptable deviation range, then the test window is flagged as fatigued pitches and a warning is generated.



*Figure 28. At risk of injury windows flagged in boxes and example warning message.*

An explanation of the sensitivity versus specificity study used to determine the acceptable deviation range is covered in chapter 7. A drawback to this method is that a change in pitch style (switching from fast ball to curve ball) may result in a false positive, but this would be easy to override during use if the coach is actively watching the pitcher alter his motion and technique based on signals and strategy in game and during practice.

#### 6.2.4: Process Analysis

To determine the valid number of pitches to use as the standard baseline window when analyzing pitching data, the team opted to run a cumulative mean analysis of maximum elbow torques and standard deviation of elbow torques for both fatigued and non-fatigued subjects. Pitching data from both the baseline data collection and induced fatigue sessions were used in this study. The cumulative mean of maximum torques and torque standard deviations for various subjects were plotted over pitch count, to observe when the data leveled off to a relatively low amount of deviation. The results of this study for Subject 1, Session 2 (no fatigue reported) and Subject 11, Session 1 (induced fatigue) can be seen in Figure 29 below.

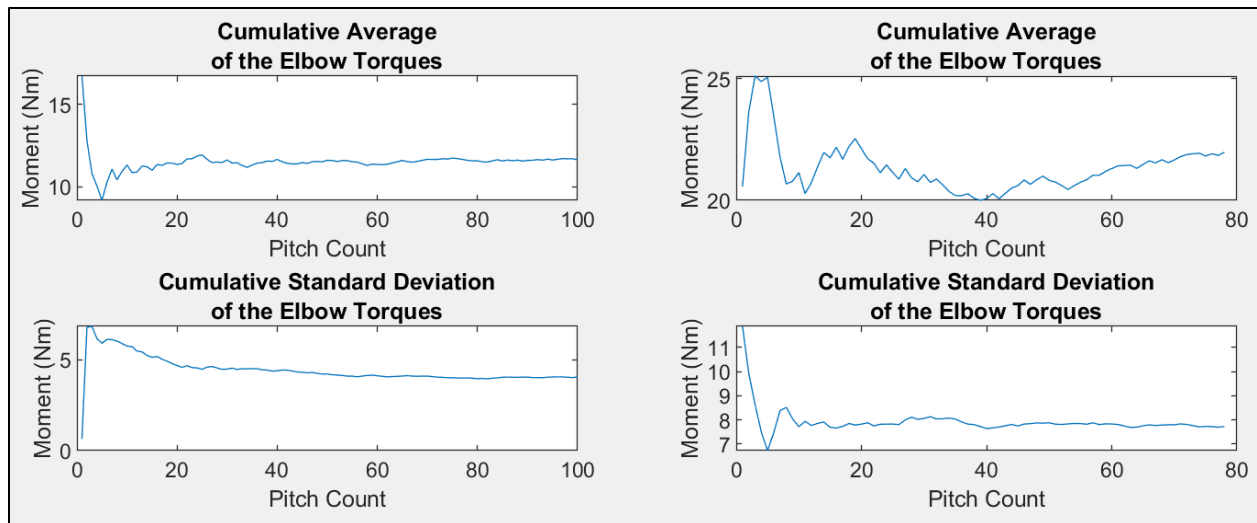


Figure 29. Cumulative mean of maximum elbow torque and standard deviation of elbow torque for Non-Fatigued Subject 1, Session 2 (left), and Induced Fatigue Subject 11, Session 1 (right).

It can be seen from the data pictured above that after the first 10 pitches, and is consistent in the other 8 data sets, the data has a drastically lower amount of deviation for each plot. From this, the team concluded that the data to be analyzed for unhealthy deviation would be after this point in any pitching session, and that these first 10 pitches would be used for the baseline window.

## 6.3: Impacts of Final Design

### 6.3.1: Economics

While the system is an initial investment for the individual or team, the cost is much lower than that of UCL repair (a direct cost) or recovery from UCL injury (an indirect cost) to the pitcher. UCL reconstruction can cost \$15,000 and require a year of physical therapy rehabilitation that may add on a minimum of \$3,000 to the cost of the reconstruction. In addition to this, baseball teams continue to be responsible for the contracts -- in excess of one million dollars -- of these injured athletes, and for athletes whose careers are ended by these catastrophic injuries, millions of dollars are lost.

To be brought to market the cost of the system may increase from the initial cost of production for the prototype, as it would benefit from better IMU technology and the incorporation of Bluetooth technology. For this project's purposes, the sensors used cost \$35.95

each, the micro SD cards were \$6.39 each, and the lithium-ion batteries were \$4.95 each. All were purchased online from SparkFun.com. However, by buying in bulk, SparkFun offers a volume order discount for quantities of 250 units and above. The total cost of the sensor system developed at low volume pricing was \$47.29. Overall the use of this system has the potential to bring about economic benefit to the users.

To outfit every pitcher in the MLB with this device, just given the materials cost, would cost \$18,000. Assuming that 30 UCL reconstructions are required in the MLB in a single year, even if the device were only able to prevent 5% of the injuries requiring surgery, there would still be a savings of \$9,000. These savings don't even consider the cost of the contracts.

We do believe that this device will serve as an out of pocket expense for athletes, teams, and organizations, as its efficacy is dependent on the way that it is decided to be used. If the system were to gain medical and trainer approval, it may be able to become covered by insurance, but this would only be if the efficacy of the device were determined high enough that it is widely preventing and predicting injury.

### 6.3.2: Environmental Impacts

At this stage in the sensor system development, there are no significant environmental impacts from use of the system itself. The environmental effects are caused by the manufacturing process of the system, and the process currently is at a very small scale resulting in no impact on the environment. If manufacturing and production increase in the future, there could be a respective increase in the environmental impact. These impacts could include the use of single use materials in the system which would increase the amount of waste produced, the energy required to produce each individual sensor system, and the use and disposal of batteries.

### 6.3.3: Societal Influence

The product is designed to monitor the level of fatigue in a baseball pitcher's elbow over time indicating when a dangerous level of injury risk has occurred. In doing so, the product would allow for baseball coaches to accurately assess the level of fatigue in the pitcher, without relying on the player to self-report this data. This systematic way of monitoring elbow fatigue could help baseball coaches and pitchers mitigate elbow injury risk by proactively resting pitchers when necessary, rather than pushing the player to his limit and risking an elbow injury

due to overuse. If the use of the product was widespread over all age groups of baseball pitchers, then the amount of UCL tears could drop significantly.

#### 6.3.4: Political Ramifications

There are no applicable political ramifications regarding the current sensor system. The purely commercial aspect of the system allows it to remain in the private sectors in its use.

In addition to use for individual pitchers, this system could be used to update the pitch count restrictions in junior level baseball. Current pitch restrictions are not based on any objective rationalizations, but if enough data were collected on fatigue points in junior pitchers, the leagues could update their regulations to better reflect the general health and safety limitations of the particular athletes.

There does exist a level of liability in bringing an injury prevention device to market. There are some injuries that the system cannot account for, such as non-fatigue induced injuries that can sometimes occur right at the start of practice. As a result, in avoiding the potential for lawsuit, it would be necessary to specify in the marketing and use of the product that this is meant only to aid in the prediction of injury. As the system itself cannot prevent injury, but it instead may provide the tools for an athlete and coach to reduce the risk of injury by informing preventive actions.

Pending improvements in the predictive abilities of the device, some teams and organizations could require the use of the device as a method of saving money by preventing injury, this would be most likely in the MLB, where the organization has a financial investment in the athletes. Additionally, were the device to become covered by health insurance, failure to use the device in conjunction with becoming injured could give the insurance company the ability to refuse to aid in the financial burden of the surgery and rehabilitation.

#### 6.3.5: Ethical Concerns

At this stage, the system is not marketable and consequently does not have a significant influence on the global market and the respective ethical impacts. The main ethical concerns pertaining to this sensor system is that the data projected to the user must be interpretable and defensible. It is important to remember that the project team has no medical qualifications and that we cannot provide information and conclusions that should be doubtlessly accepted without

a physician's opinion. Another ethical concern regarding this project is the IRB approval required for the methods used. This approval from the IRB ensures that all methods carried out during this project are ethical for all subjects.

### 6.3.6: Health and Safety Issues

As previously stated, UCL injuries are one of the most prominent injuries seen in baseball pitchers. This product could possibly modify the way that pitchers monitor overuse in their pitching arm, promoting healthier practices concerning elbow health. In all, the product could decrease the likelihood of a UCL tear due to fatigue and overuse in baseball pitchers. It is possible that pitchers and pitching staff could rely too heavily on the device, which may lead to overconfidence in the accuracy in the device, and therefore result in injury. While this sensor system can predict UCL injuries, it is not to be used as a method that will completely stop the injury from occurring.

### 6.3.7: Manufacturability

This system is developed using off the shelf sensors which are already on market, and are comparable to the IMUs in analogous devices such as the Motus systems. The data analysis runs through a MATLAB script which is written in C format. Given a reasonable budget and proper engineering experience, the system would be reproducible. Increased budget and quantity of systems produced would allow for smaller sensors with better adhesive affixation.

### 6.3.8: Sustainability

The production of the sensor system contains one main component that would impact sustainability. The accelerometer contained in the system is battery powered, which must be discarded eventually. With further development, the accelerometers could be rechargeable or be powered by a renewable energy source. A future sustainability impact that could arise is the energy required to produce the sensor systems on the level of the manufacturer if the system were to be available on the market.

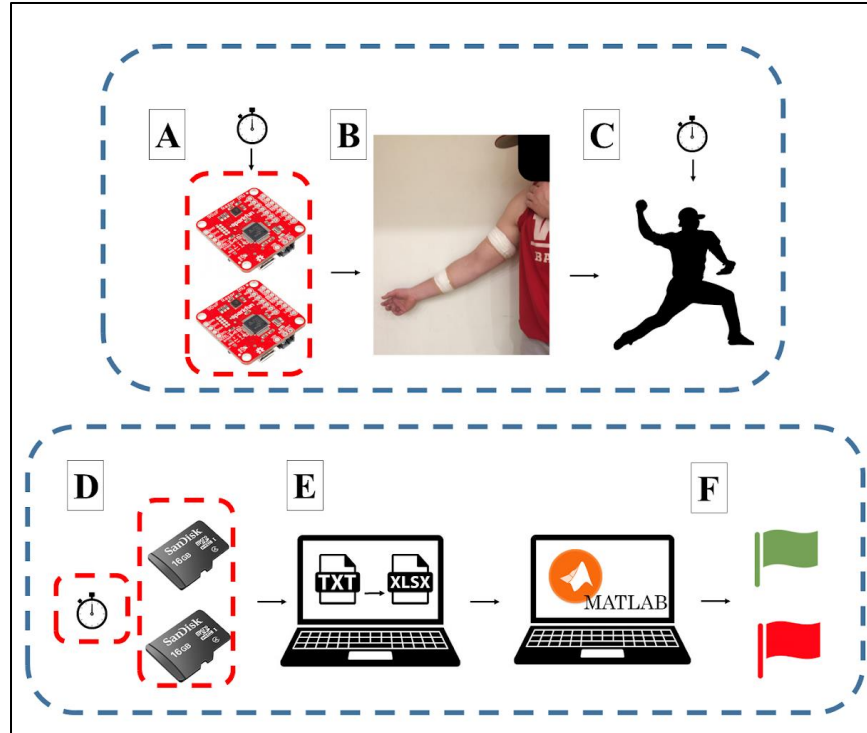
# Chapter 7: Final Design and Validation

## 7.1: Final Design Architecture

The final design of the sensor system addresses the needs from the final, revised client statement for the project. The statement, from Section 3.4, is as follows:

The goal of this project is to develop a low profile wearable sensor system for pitchers to use during games and practice sessions. The sensor system will measure the forces and torques at the shoulder and elbow during the pitch through a system of two IMUs. The system will analyze these measured data to identify variation from the individual's baseline motions to then indicate fatigue through deviation from the baseline. The device will provide easy to interpret feedback to coaches and pitching staff, enabling them to determine when athletes are reaching a point of fatigue that places the athlete at increased risk for injury.

The final design for the system can be broken down into two subsystems: the hardware subsystem, and the software subsystem. The hardware subsystem is made up of two IMU's, each with a 16 gigabyte micro SD card and lithium-ion battery, and a stopwatch. The IMU's used in the final design are the 9DoF Razor IMU, which features a MPU-9250 9DoF motion sensor and SAM D21 microprocessor all contained on one breakout board. The 9DoF Razor has a measurement range of +/- 16 G's and +/- 2000 degrees/second, and logs data locally to the micro SD card at a rate of about 142 Hz. The software subsystem includes the excel files that contain the raw data from the IMU micro SD cards, and the code generated for analyzing the motion data through MATLAB software. A concept of operations diagram for the use of the sensor system is depicted in Figure 30 below.



*Figure 30. Concept of Operations Diagram for the final sensor system design. System operation follows (A) synchronized activation of sensors and stopwatch, (B) placement of sensors on pitching arm, (C) pitching by user with time points of pitches logged on stopwatch, (D) retrieval of data from stopwatch and sensors, (E) transfer of time/mechanics data into MATLAB for analyzation, and (F) indication of increased levels of fatigue during pitching related to injury risk.*

To begin operating the system, the user turns on both sensors at the same time, and starts the stopwatch. Next, with the assistance of another person, both sensors are placed at the center of mass of the forearm and upper arm, using arm segment lengths and anthropometric data to calculate the exact locations. The sensors are attached to the flexed arm by first wrapping pre-wrap around the arm and sensor, followed by a layer of athletic tape which covers the top and bottom of the sensor. The user then pitches throughout a game or practice, and the stopwatch is lapped by another person at the beginning of each pitch. At the end of the pitching session, the sensors are removed, turned off, and the stopwatch is stopped. This ends the data collection phase of the system's operation.

The micro SD cards are removed from the sensors, and inserted into a computer to download the motion data in a text (.txt) file. The text file is then converted to an excel file (.xlsx). The time points from the stopwatch are put into a separate excel file. Both the motion



data and time point excel files are uploaded into MATLAB software for analysis, as this is the software that was utilized by the team to write the code for data processing and analyzing. Realistically, any coding language could have been used for this. The MATLAB code analyzes the pitching motion and highlights groups of pitches where the deviation in torque is too high in comparison to the user's baseline deviation, indicating to the user where a potential injury risk has occurred. This ends the data analysis phase of the system's operation.

A more detailed look at the elements and interfaces of the sensor system's final architecture is shown in the block diagram in Figure 31 below.

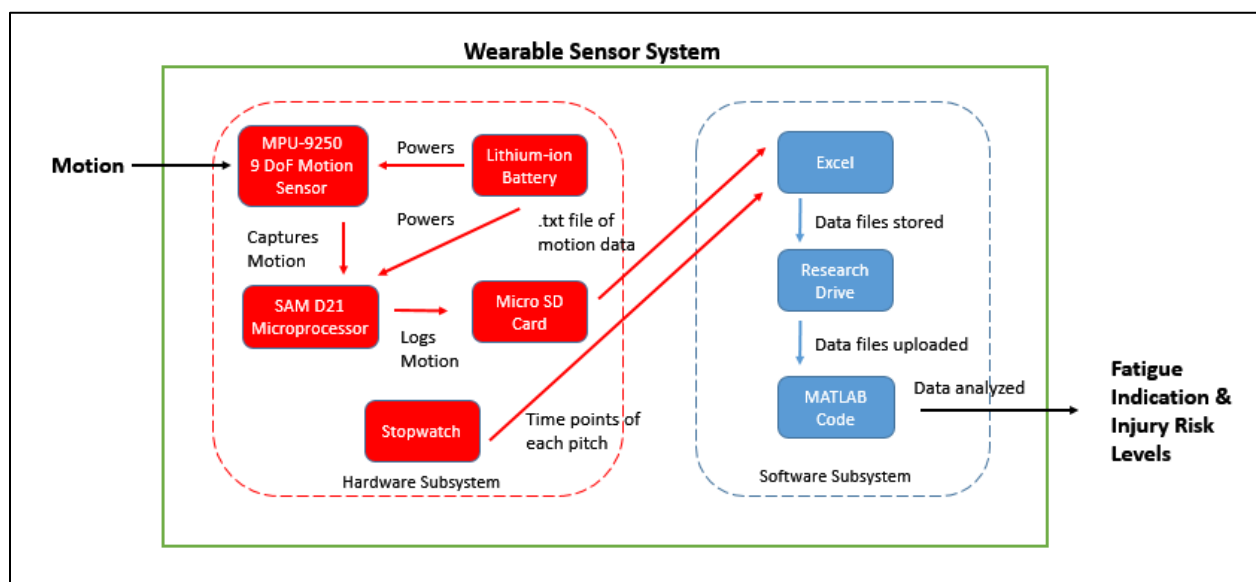


Figure 31. Block Diagram depicting functions of elements and interfaces in the sensor system.

The external input to the system, which interfaces with the hardware subsystem, is the user's pitching motion. The MPU-9250 motion sensor captures this motion and signals the linear accelerations and angular velocities to the SAM D21 microprocessor at 1000 Hz. Both are powered by the lithium-ion battery connected to the breakout board of the IMU. The microprocessor then logs these data points onto the micro SD card at a frequency of 142 Hz. The external stopwatch is used in conjunction with the IMUs, logging time points for each pitch. After the motion of the pitching session has concluded, the data from the micro SD cards in the form of a text file, and the time points from the stopwatch, are transferred to separate excel files. After the excel files have been made for the pitching session, they are stored on a network research drive. The excel files from the research drive are then uploaded to MATLAB software

containing the code written for the project. The MATLAB code written for the project uses the time point data to highlight approximately where each pitch starts in the motion data. This, in conjunction with the equations of motion outlined for the project, is used to calculate the maximum force at the elbow in each pitch. The maximum force of each pitch is then used to calculate the maximum torque at the elbow generated in each pitch. The deviation of torque values from the baseline pitches of the session are used to establish a baseline deviation value for the user. We decided that elbow torque would be the most meaningful metric to analyze as it will most closely represent how the UCL is being strained. Next, a sliding window analysis is used to investigate the deviation of torque values throughout the rest of the pitching session. If a torque deviation for a subset of pitches is markedly higher than the set baseline deviation, the code flags this to the user, prompting them to check if the pitcher has fatigued. This final output of the system indicates instances of potential fatigue based injury risk of the user.

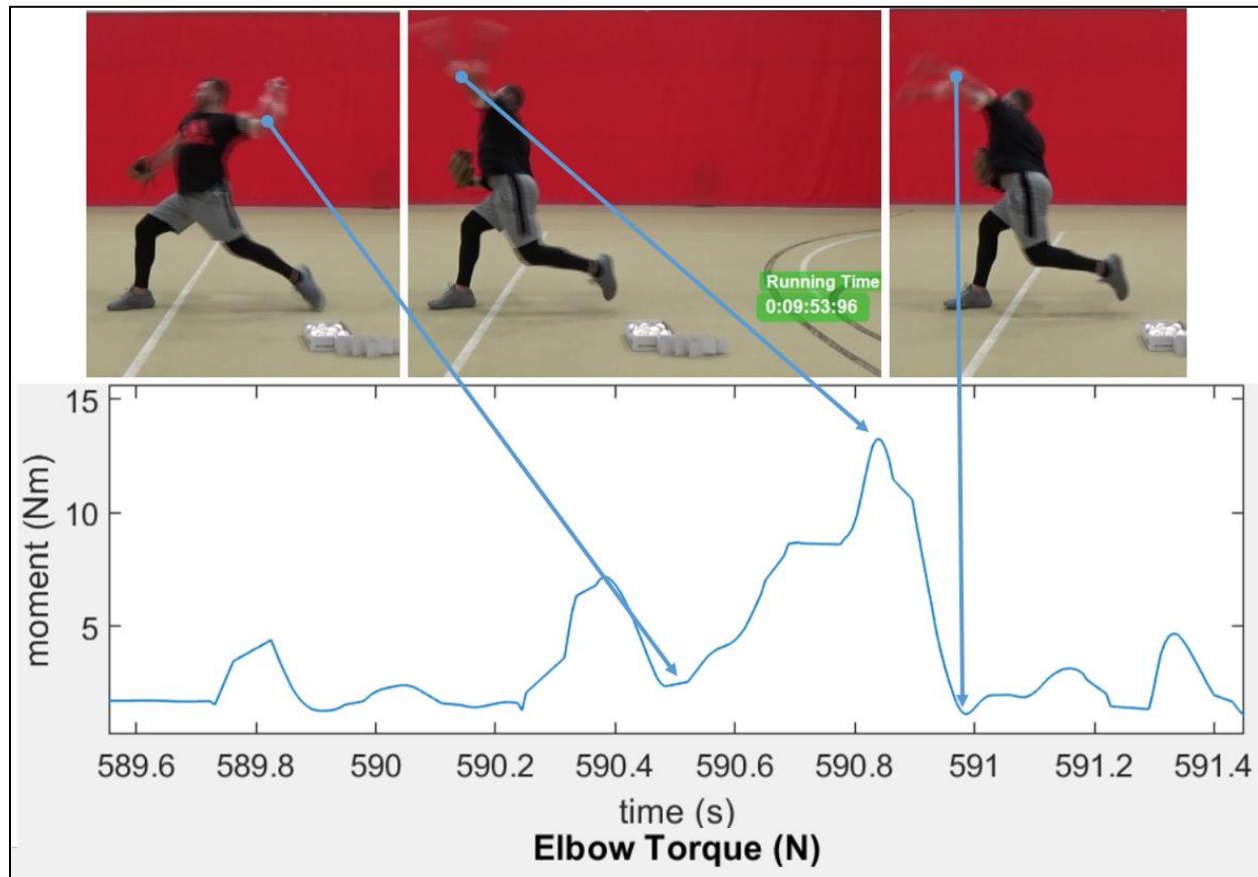
## 7.2 Design Validation

To validate the results of the system, two protocols were performed. The tests were concerned with validating that the system was detecting maximum forces and torques at the correct phases of the pitching cycle and determining sensitivity and specificity values for the system.

### 7.2.1 Maximum Force/Torque System Validation

To validate that the motion data logged and analyzed by the system coincided with the motion of the pitches happening in the real world, an external video motion capture system was used to highlight the time point of expected maximum elbow torque in the pitching cycle. Kinovea is a free motion tracking and video analyzing software that was used to slow down the pitch video data while also keeping a running time log for the video [43]. The video camera started recording at the same time the sensors were turned on for the pitching session so that the time data for both sources would line up within seconds of each other (the sensors typically have a two second lag after being switched on before logging motion data). The videos for various pitches in the session were slowed down around the late cocking and acceleration phases of each pitch as the moment of maximum external rotation at the shoulder, and coincidentally the maximum moment of shoulder and elbow torque, occurs between the transition of these two

phases. This time point of maximum external rotation of the arm during the pitch cycle from the video's running time log was compared with the time point of maximum elbow torques from the analyzed pitching data. An example of this is shown in Figure 32 below.



*Figure 32. Maximum external shoulder rotation in Subject 10, Session 1, from Kinovea video data compared with analyzed maximum elbow torque data from sensor system.*

It can be seen from the figure above that the moment of maximum external rotation occurs at 9:53:96 of the pitching session, or 593.96 seconds. The maximum elbow torque for this pitch logged by the sensors was at 590.80 seconds. Part of the discrepancy between the two time points can be attributed to the initial lag in the sensors when being switched on, but as the total difference between the time points was only about 3 seconds, this study shows that the sensor data matches the real world motion.

### 7.2.2 Sensitivity Study

To both validate the deviation level set for flagging unhealthy deviation and determine the sensitivity of the system in detecting fatigue, the team conducted a sensitivity vs. specificity study. Three different deviation levels were tested in the study: 0.1%, 1%, and 10%. The sensitivity of a test is the probability that the test will detect the condition it is testing for accurately, while the specificity of a test is the opposite, measuring the probability that the test will correctly identify the absence of the condition. Two other metrics measured in this study were the positive predictive value (PPV) and negative predictive value (NPV) of the system. The PPV informs about the ratio of true positives and false positives, while NPV informs about the ratio of true negatives to false positives. The PPV and NPV are similar to sensitivity and specificity but have marked differences; sensitivity and specificity measure the probability that a test will accurately detect the condition being tested for based off of the known presence of the condition, while PPV and NPV measure the probability of the condition's presence based off of the results of the test.

To set up the study, negative fatigue and positive fatigue data sets were first established. The team used sets of pitching data from the baseline data collection sessions where pitchers self-identified on their post-session surveys as having little to no fatigue as the non-fatigued (negative) group for the study. For the fatigued (positive) group, subject 11's data from the induced fatigue session was used. Two assumptions were made when outlining the positive and negative groups: all pitch windows during the induced fatigue protocol following the arm cycle sprints would be classified as fatigued, and when a subject was fatigued they would constantly show raised levels of deviation. These assumptions were made due to the fact that fatigue in subjects could only be self-identified, and there needed to be a clear way to distinguish the expected positive and negative data sets. The test setup is outlined in Table 8 below. Each pitch window analyzed by the sliding window analysis was treated as either an expected positive or expected negative instance of fatigue.

*Table 8. Parameters for Sensitivity vs. Specificity Study.*

Deviation Level	0.1 %, 1%, 10%	
Sliding Window Size	6 Pitches	
Positive Group (Induced Fatigue)	Sub. 11, Ses. 1 (all pitches following the first induced arm fatigue protocol)	20 total windows
Negative Group (No Fatigue)	Sub. 1, Ses. 2 Sub. 3, Ses. 1 Sub 7, Ses. 1 Sub 8, Ses. 1 Sub. 11, Ses 1 (all pitches preceding the first induced arm fatigue protocol)	69 total windows

The pitch data for maximum elbow torque from the subject sessions detailed in the table above was run through the sliding window analysis for deviation at a flagging level of 0.1%, 1%, and 10%, to see if the system could blindly detect and identify fatigued data. The results from these analyses were recorded, tallying the true positives (windows flagged as fatigue when fatigue was expected), false positives (windows flagged as fatigue when no fatigue was present), true negatives (windows not flagged when no fatigue was present), and false negatives (windows not flagged where fatigue was present). The results from this analysis are recorded in Table 9 below.

Table 9. Results from the Sensitivity Study Analyzing at 0.1%, 1%, and 10% Deviation.

Deviation Level	0.1%	1%	10%
True Positive	10	10	3
False Positive	8	7	4
True Negative	61	62	65
False Negative	10	10	17
Sensitivity	50%	50%	15%
Specificity	88.4%	89.9%	94.2%
PPV	55.6%	58.8%	42.9%
NPV	85.9%	86.1%	79.3%

A Receiver Operator Characteristic (ROC) curve was generated from the data of the study, which can be seen below in Figure 33.

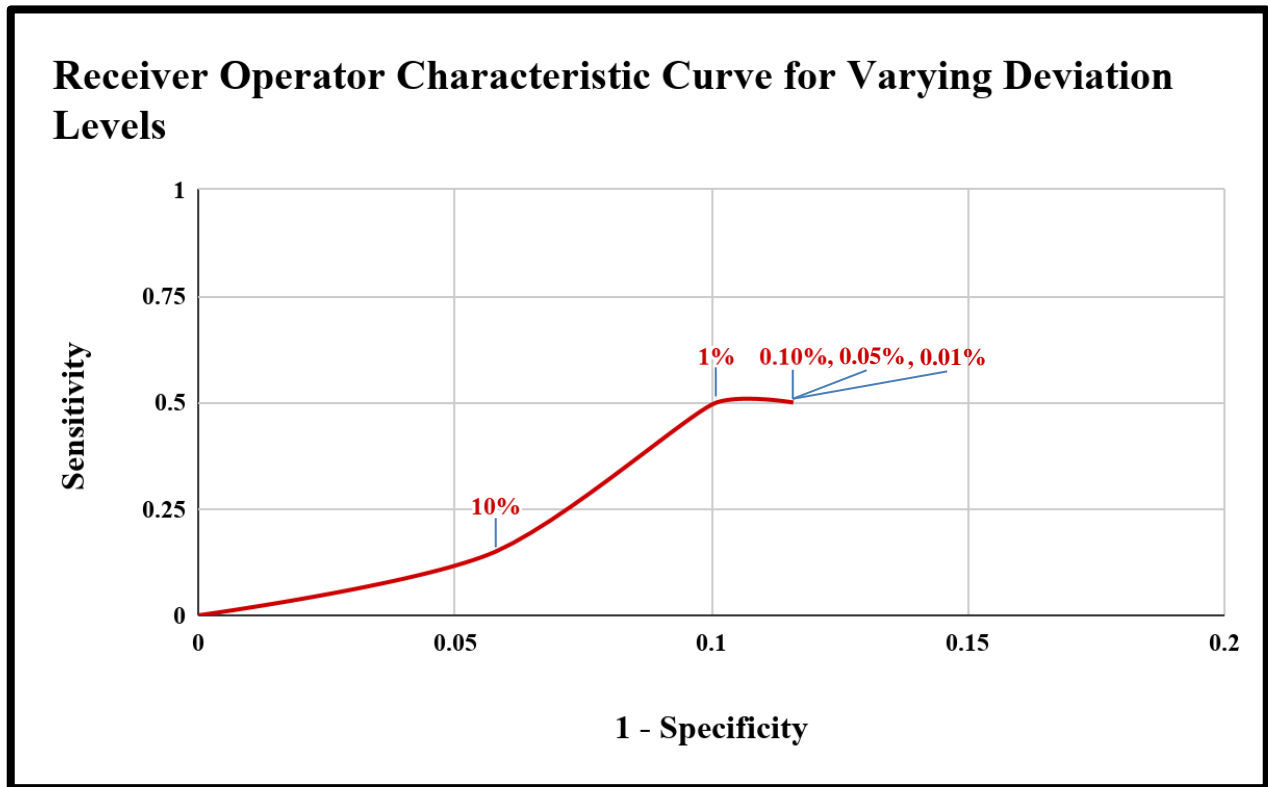


Figure 33. ROC Curve depicting the evaluation of the Sensitivity and Specificity Values for the system when run at 0.01%, 0.05%, 0.1%, 1%, and 10% deviation detection.

Based on the results of the ROC curve, a deviation level of 0.1% was selected for use in analysis by the system. This is because the ROC curve levels off to the most balanced value at 0.1%, with a sensitivity value of 50% and specificity value of 88.4%. Although deviation levels of 0.05% and 0.01% produced equal values for sensitivity and specificity, it might be that with larger data sets, that these deviations could become insignificant, and thus 0.1% was determined the greatest level of deviation with the most acceptable sensitivity and specificity. However, this indicates that the system needs to have an increased ability to both detect when fatigue is present, and produce a positive indicator in this event.

## 7.3 Study Limitations

Throughout the project and validation studies, there were generalizations and assumptions made that should be noted. These limitations of the project can be broken down into three main categories: generalizability of subjects, pitch type assumptions, and validation assumptions.

### 7.3.1: Generalizability of Subjects

In the project, the human subject testing was conducted with 11 collegiate level baseball pitchers. All of the data then can only draw conclusions about the operation of the system with a small group of experienced pitchers. The variation levels in pitching sets for experienced pitchers may behave differently than that of inexperienced ones. Ideally, the system would be able to be used by all levels of pitchers including inexperienced youth pitchers. To address this, future work on the system should include expanded human subject testing, not only with the addition of younger subjects of youth and high school league players, but with more subjects in general.

### 7.3.2: Pitch Type Assumptions

There were two main limitations concerning pitch type in the human subject testing for the project. During baseline data collection, the team did not know what kinds of pitches were being thrown during the sessions. This was due to the nature of the sessions, as we were sitting in on live baseball practices and could not ask the subjects to only throw one type of pitch, or have

the subjects inform us about the pitch types being thrown while the session was occurring. The second was that during the induced fatigue sessions, the team had the ability to instruct the subjects to only throw one type of pitch. Two issues arise here: the first is that the system cannot discern between different styles of pitch, and the second is that the pitching styles between the baseline data collection sessions and the induced arm fatigue sessions do not match.

Subsequently, the team does not understand if there are impacts of different pitch types, or changes between pitch types during a session, on torque data and arm mechanics deviation.

Future work on the system should include human subject testing with individual sets of each kind of pitch, and sessions with specified pitch changeups, to determine the system's feasibility with variable pitch style.

### 7.3.3: Validation Assumptions

During the sensitivity study, three assumptions were made concerning the induced fatigue data. The first assumption made was that all pitches following the arm cycle protocols during the induced fatigue sessions were classified as fatigued data. The second assumption made was that when a pitcher was fatigued, their arm mechanics would continue to have higher levels of deviation, rather than leveling out to one consistent deviation level that would then not be flagged by the system; the concern with this assumption is that if the pitcher compensated for their fatigue by falling into consistent poor form, the deviation levels would again level out and not be flagged by the system. The third assumption was that the team relied on self-reported fatigue levels from the subjects, which is a subjective value. We did not have a fatigue validation system during our human subject testing. For example, surface electromyography based muscle fatigue detection is a systematic way to eliminate subjectivity in these measurements. Future work on the system should include more induced fatigue subject testing with the use of a systematic fatigue detection method, such as surface electromyography, with an increased amount of subjects.

### 7.3.4: Limitations Conclusion

As this project completed the early stages of design and testing to validate the system's main concept of predicting injury risk by detecting arm mechanic deviations from increased fatigue levels, various assumptions had to be made. However, this is not to say that the results of



the testing conducted on the system are invalid. The learnings from the human subject testing and assumptions made during these sessions should be used to inform future work on the project to continue to improve the feasibility and efficiency of the system. Ultimately, human subject testing with the system should be expanded to include more subjects from all levels of pitching experience, and include more validated fatigue data collection and analysis.

# Chapter 8: Conclusions and Recommendations

## 8.1: Conclusions

Elbow injury rates, specifically those related to the UCL, are continuously increasing in baseball pitchers of all ages. Injuries pertaining to the UCL can have career ending effects in baseball pitchers, and have a difficult recovery process because of the UCL's importance in stabilizing the elbow joint. To stabilize the joint during a baseball pitch, a varus torque is generated by the UCL to counteract the valgus torque experienced in the elbow. The lack of reliable preventive strategies for UCL injuries is what results in the commonly necessary reconstructive surgery for UCL injuries. The current approach to preventing UCL injuries are exercises, motion analysis, or braces. These approaches are limited due to the fact that they do not relate fatigue to the causes of injury. The goal of this project was to develop a wearable sensor system to identify the risk of joint injury in baseball pitchers through deviations of biomechanics and the relation to fatigue.

The wearable sensor and data analysis system worked together to predict the point at which fatigue caused an unhealthy amount of deviation of forces and torques in the elbow and shoulder that could cause injury. The system was used and tested using results from data collection sessions with collegiate baseball pitchers. From the collected data, the system identified increased variation in pitching mechanics which is correlated with fatigue by first calculating baseline forces and torques of the joints and analyzing the deviation throughout a pitching session, with exaggerated results from induced fatigue sessions. Based on a sensitivity study using the results, it was concluded that an unhealthy deviation in the joint forces and torques that could lead to injury is 0.1%.

The developed sensor system improved upon the limitation of current market strategies by correlating the risk of injury to fatigue. Though this project was focused on baseball pitchers, this technology can be applied to a variety of sports to prevent joint injuries. Through further development, this system could be used as a real world injury preventive strategy with various applications.

## 8.2: Future Recommendations

The design of this sensor system project was successful in meeting the requirements outlined in the problem statement, but could be improved upon in certain areas. The team recommends the following improvements for future development:

- **Increased efficiency of sensors:** The hardware portion of this system could be improved by the use of smaller sensors that do not require an external battery to create a less cumbersome system. The sensors could also have a higher quality microprocessor to increase data logging rates to match the sampling rate of the motion sensors, which would ensure that all possible data points are collected. An example of a better sensor to be used is the Blue Thunder sensor by IMeasureU, but was too costly for this project's purposes.
- **Real-Time Feedback:** To be effectively used for game situations, this system should have efficient code that will run in under one minute so coaches are able to view and interpret results between each pitch. A Bluetooth connective sensor would also eliminate the need to connect to a computer in order to analyze data and receive results, which is also pertinent for game applications and use.
- **Compact Design:** Ease of use is an important aspect for this sensor system, and creating a system that requires no effort for assembly would greatly increase the appeal for this device. A more compact design would require no wrapping and taping, and would be able to be applied without assistance. An example that would be applied is using sticker-like sensors or sensors that fit into a compression sleeve that would require minimal effort to put on and would be discreet and comfortable during play.
- **Validation:** Though this system can detect when fatigue is not present in the joints very well, it must be improved to better detect and report when fatigue is present since fatigue is correlated to the risk of injury. To increase the sensitivity and PPV of the system, more fatigue data must be collected with the amount of fatigue validated by an external source such as surface electromyography based muscle fatigue detection to confirm the existence, and level, of fatigue in a subject. This would eliminate the large assumptions made in the original sensitivity study that the team conducted resulting in more accurate results, as the team relied on self-identification of fatigue levels in the subjects. This data could then be used to investigate the efficiency and accuracy of the system's methods of

analyzing unhealthy deviation, the level of deviation set as the indicator of unhealthy fatigue, and ultimately increase the sensitivity and PPV of the system.

- **More Human Subject Testing:** As stated in section 7.3, the subject data collected during this project was from a set of 11 collegiate level pitchers. Ideally, testing should be conducted with the system on an increased number of subjects. This testing should include subjects with varying levels of pitching experience, from youth pitchers all the way up to professional pitchers.

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# Appendices

## Appendix A: Equations of Motion

### Lower Arm Segment Equations of Motion

$$-\vec{F}_{elbow} + m_{forearm} * \vec{g} = m_{forearm} * \vec{a}_{forearm} \quad (\text{Eq.1})$$

Variables:

$$m_{forearm} = (\text{body weight} * 0.022) + \text{ball weight} \quad (\text{Eq.2})$$

$$\vec{g} = 9.81\text{m/s}^2 \quad (\text{Eq.3})$$

$\vec{a}_{forearm}$  is given for Razor sensors

$$\vec{a}_{forearm} \text{ for Polhemus} = \frac{dv}{dt} \quad (\text{Eq.4})$$

$$v = \frac{dx}{dt} \quad (\text{Eq.5})$$

$t = \text{time}$

$x = \text{position coordinate}$

\*=term by term multiplication

$$I * \alpha = -\tau_{elbow} + (\overrightarrow{r_{elbow}} \times \vec{F}_{elbow}) \quad (\text{Eq.6})$$

Variables:

$$I = \frac{1}{12} * m_{forearm} * \text{forearm length}^2 \quad (\text{Eq.7})$$

$$\alpha = \frac{d\omega}{dt} \quad (\text{Eq.8})$$

$\omega$  is given for Razor sensors

$$\omega \text{ for Polhemus} = \frac{d\theta}{dt} \quad (\text{Eq.9})$$

$t = \text{time}$

$$\overrightarrow{r_{elbow}} = \text{forearm length} * 0.430 \quad (\text{Eq.10})$$

\*=term by term multiplication

X=cross product

### Upper Arm Segment Equations of Motion

$$\vec{F}_{shoulder} + \vec{F}_{elbow} + m_{upper arm} * \vec{g} = m_{upper arm} * \vec{a}_{upper arm} \quad (\text{Eq.11})$$

Variables:

$$m_{upper arm} = (\text{body weight} * 0.028) \quad (\text{Eq.12})$$

$$\vec{g} = 9.81\text{m/s}^2 \quad (\text{Eq.3})$$

$\vec{a}_{upper\ arm}$  is given for Razor sensors

$$\vec{a}_{upper\ arm\ for\ Polhemus} = \frac{dv}{dt} \quad (\text{Eq.13})$$

$$v = \frac{dx}{dt} \quad (\text{Eq.5})$$

$t = \text{time}$

$x = \text{position coordinate}$

$\ast = \text{term by term multiplication}$

$$I \ast \alpha = \tau_{shoulder} + \tau_{elbow} + (\overrightarrow{r_{shoulder}} \times \vec{F}_{shoulder}) + (\overrightarrow{r_{elbow}} \times \vec{F}_{elbow}) \quad (\text{Eq.14})$$

Variables:

$$I = \frac{1}{2} \ast m_{upper\ arm} \ast \text{radius of bicep}^2 \quad (\text{Eq.15})$$

$$\alpha = \frac{d\omega}{dt} \quad (\text{Eq.8})$$

$\omega$  is given for Razor sensors

$$\omega\ for\ Polhemus = \frac{d\theta}{dt} \quad (\text{Eq.9})$$

$t = \text{time}$

$$\overrightarrow{r_{shoulder}} = \text{upper arm length} \ast 0.564 \quad (\text{Eq.16})$$

$$\overrightarrow{r_{elbow}} = \text{forearm length} \ast 0.430 \quad (\text{Eq.10})$$

$\ast = \text{term by term multiplication}$

X=cross product

# Appendix B: Informed Consent Agreement for Participation in a Research Study - As Approved by the Worcester Polytechnic Institutional Review Board

**Investigator: Julia Dunn; Lauren Guertin; Madison Michaud**

**Contact Information: gr-baseballmqp@wpi.edu; jadunn@wpi.edu; leguertin@wpi.edu; mdmichaud@wpi.edu**

**Title of Research Study: Injury Prevention in Baseball Pitching**

**Sponsor: Worcester Polytechnic Institute**

**Introduction:** You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

**Purpose of the study:** The purpose of this study is to understand the learning and coaching of pitching mechanisms with the goal of identifying potential causes of the mechanism which causes acute elbow injury. The team intends to use the collected information to develop a system to help prevent baseball pitching elbow injuries.

## **Procedures to be followed:**

**Duration of Subject's Participation:** The study runs until 19-Apr-2018. All study participants will be invited and encouraged to participate for the entire duration of the study. Level and time of participation may fluctuate throughout the study (participation requirements will not be steady the entire study)

**Data Collection and Interviews:** Subjects may be asked to participate in a structured interview. All subjects will be made aware that anything they say may be used as a part of the study, with the exception of identifying information. Prior to every interview the subject will be read the Study Aim Statement, and then be asked all interview questions.

**Study Aim Statement:** The goal of this data collection and interview is to better understand pitching mechanics and the mechanisms which lead to elbow injury during pitching. Do you have any questions for us before we get started? Do you understand what is being asked of you?

**Player/Pitcher Interview:** These questions will gauge level of play, competition history, history of and current injuries. These questions will also assess the daily athletic performance throughout the trials.

**Procedures for Data Collection:** Throughout data collection sessions the pitchers will be asked interview questions regarding health and fatigue. Investigators will attach superficial inertial measurement units to the arm and chest using athletic adhesives. The pitchers will pitch according to their practice schedule. During some data collection sessions, the subjects will be asked to participate in a controlled arm fatigue protocol using an arm cycle. This is a pre-existing method which is used in arm fatigue studies. The purpose of the arm fatigue protocol is to safely simulate muscle fatigue. All protocols are approved by the subject's coach prior to the subject's participation in their first data collection session.

**Photos:** Photos will be taken of the subject pitching in practice going through specific pitching exercises. All motions recorded will be on the volition of the player. Subjects may be asked to apply fiduciary markers and/or EMT systems trackers to specific boney landmarks during the captured motions. These trackers will not inhibit or affect the motion of the subject.

**Risks to study participants:** Participation in this study will not place participants at any greater risk than is normally experienced in their life.

**Benefits to research participants and others:** There is no direct benefit to participants of this study during the course of the study.

**Alternative procedures or treatments available to potential research participants:** This study is not offering or performing any form of treatment to the patients. All treatments are at the discretion and cost of the participants.

**Record keeping and confidentiality:** All data collected will be maintained and kept in a private folder among the research team. All photos will be edited to cover identifying features prior to any form of analysis. All interviews will be documented using general information about the interviewee (including age, role and experience with the subject matter). All records will be kept by the faculty advisor of this project for three years following the completion of the project. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or it's designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

**Compensation or treatment in the event of injury:** Because the risk involved with participation in this study is no higher than would be expected normally the group does not offer any compensation or treatment in the event of an injury. You do not give up any of your legal rights by signing this statement.

**For more information about this research or about the rights of research participants, or in case of research-related injury, contact:** Please contact the research team via email as listed at the top of this form. With additional questions or concerns please contact the IRB Chair (Professor Kent Rissmiller, Tel. 508-831-5019, Email: [kjr@wpi.edu](mailto:kjr@wpi.edu)) or Gabe Johnson, Human Subjects Administrator ([gjohnson@wpi.edu](mailto:gjohnson@wpi.edu), (508) 831- 4989).

**Your participation in this research is voluntary.** Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

**You must be 18 or older to participate in this study**

**By signing below,** you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

---

Study Participant Signature

Date: \_\_\_\_\_

---

Study Participant Name (Please print)

---

Signature of Person who explained this study

Date: \_\_\_\_\_

**Additional clauses to add to Consent Agreements, as appropriate:**

The treatment or procedures used in this research may involve risks to the subject (or to an embryo or fetus, if the subject is or may become pregnant), which are currently unknown or unforeseeable.

Additional costs to the subject that may result from participation in this research include: (list).

Significant new findings or information, developed during the course of the research, may alter the subject's willingness to participate in the study. Any such findings will be promptly communicated to all research participants.

Should a participant wish to withdraw from the study after it has begun, the following procedures should be followed: (list). The consequences for early withdrawal for the subject and the research are: (list).

**Special Exceptions:** Under certain circumstances, an IRB may approve a consent procedure which differs from some of the elements of informed consent set forth above. Before doing so, however, the IRB must make findings regarding the research justification for different procedures (i.e. a waiver of some of the informed consent requirements must be necessary for the research is to be "practicably carried out.") The IRB must also find that the research involves "no more than minimal risk to the subjects." Other requirements are found at 45 C.F.R. §46.116.

## Appendix C: Subject Intake Survey

Adapted from Kerlan-Jobe Orthopedic Clinic Shoulder & Elbow Score

Name \_\_\_\_\_ Age \_\_\_\_\_ Sex \_\_\_\_\_  
 Dominant Hand (R) \_\_\_\_\_ (L) \_\_\_\_\_ (Ambidextrous) \_\_\_\_\_  
 Date of Examination \_\_\_\_\_ Sport \_\_\_\_\_ Position \_\_\_\_\_  
 Years Played \_\_\_\_\_  
 Subject # (for investigator use only) \_\_\_\_\_

Height (feet and inches) \_\_\_\_\_  
 Weight (pounds) \_\_\_\_\_  
 Forearm Length \_\_\_\_\_  
 Upper Arm Length \_\_\_\_\_  
 Collar Length \_\_\_\_\_

Please answer the following questions related to your history of injuries to YOUR ARM ONLY:

	YES	NO
1. Is your arm currently injured?	<input type="radio"/>	<input type="radio"/>
2. Are you currently active in your sport?	<input type="radio"/>	<input type="radio"/>
3. Have you missed game or practice time in the last year due to an injury to your shoulder or elbow?	<input type="radio"/>	<input type="radio"/>
4. Have you been diagnosed with an injury to your shoulder or elbow other than a strain or sprain?	<input type="radio"/>	<input type="radio"/>
If yes, what was the diagnosis? _____	<input type="radio"/>	<input type="radio"/>
5. Have you received treatment for an injury to your shoulder or elbow?	<input type="radio"/>	<input type="radio"/>
If yes, what was the treatment? (Check all that apply)	<input type="radio"/>	<input type="radio"/>
<input type="radio"/> Rest <input type="radio"/> Therapy <input type="radio"/> Surgery (please describe): _____		

Please describe your level of competition in your current sport:

(Use Professional Major League, Professional Minor League, Intercollegiate, High School as the choices)

6. What is the highest level of competition you've participated at? \_\_\_\_\_  
 7. What is your current level of competition? \_\_\_\_\_



8. If your current level of competition is not the same as your highest level, do you feel it is due to an injury to your arm?

☐ ☐

Please check the ONE category only that best describes your current status:

- ☐ Playing without any arm trouble
- ☐ Playing, but with arm trouble
- ☐ Not playing due to arm trouble

Instructions to athletes:

The following questions concern your physical functioning during game and practice conditions. Unless otherwise specified, all questions relate to your shoulder or elbow. Please answer with an X along the horizontal line that corresponds to your current level.

1. How difficult is it for you to get loose or warm prior to competition or practice?



2. How much pain do you experience in your shoulder or elbow?



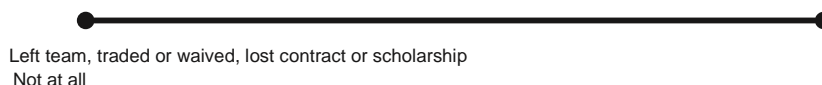
3. How much weakness and/or fatigue (i.e., loss of strength) do you experience in your shoulder or elbow?



4. How unstable does your shoulder or elbow feel during competition?



5. How much have arm problems affected your relationship with your coaches, management, and agents?



The following questions refer to your level of competition in your sport. Please answer with an X along the horizontal line that corresponds to your current level.

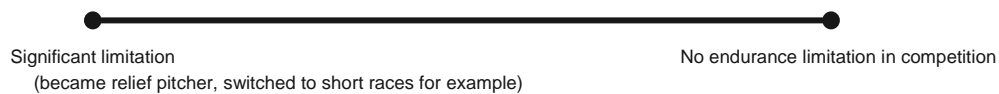
6. How much have you had to change your throwing motion, serve, stroke, etc., due to your arm?



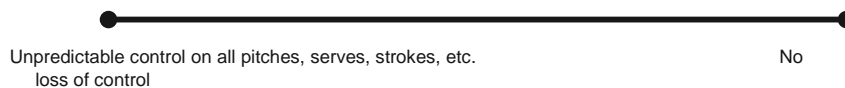
7. How much has your velocity and/or power suffered due to your arm?



8. What limitation do you have in endurance in competition due to your arm?



9. How much has your control (of pitches, serves, strokes, etc.) suffered due to your arm?



10. How much do you feel your arm affects your current level of competition in your sport (i.e., is your arm holding you back from being at your full potential)?



Kerlan-Jobe Orthopedic Clinic Shoulder & Elbow Score  
Functional Assessment Tool for the Upper Extremity 1  
Vol. 38, No. 5, 2010

## Appendix D: Baseline Data Collection Protocol

### 1. Purpose

The purpose of this procedure is to measure the loads, torques and speeds at the elbow/shoulder using our sensor system to gather anecdotal data with respect to fatigue and pain. The data will be used to define personal baselines and track the relationship between fatigue and gathered metrics.

### 2. Scope

The scope of this procedure will apply to all voluntary subjects. This procedure will include tests and research completed in the field using inertial measurement units (IMU) and motion tracking equipment.

### 3. Responsibility

The research group and coaches of the voluntary subjects will be responsible for setting up experimental sessions.

### 4. Materials

The materials and equipment used in this testing are as follows:

- Razor Units (2)
  - Razor Sensors
  - Battery
  - Micro SD Card
- Athletic Tape
- Pre-Wrap
- Stopwatch
- Baseball
- MATLAB

### 5. Procedure

Patient Data:

1. Assign subject to a patient number
2. Request subject to complete the intake survey
3. Measure and record on intake survey
  - 3.1. Forearm: ulnar styloid to medial elbow epicondyle
  - 3.2. Upper arm: medial elbow epicondyle to acromion process
  - 3.3. Relaxed bicep circumference

Set Up:

1. Turn on Sensor 1 and Sensor 2 at the same time and begin a timer

2. Attachment of sensors to subject.
  - 2.1. Sensor attachment locations
    - 2.1.1. Place Sensor 1: the center of mass of the inner forearm
    - 2.1.2. Place Sensor 2: the center of mass of the inner upper arm
  - 2.2. Sensor attachment
    - 2.2.1. Hold sensor at specified location
    - 2.2.2. Wrap pre wrap around sensor and limb twice
    - 2.2.3. Secure using athletic tape while subject slightly flexes each segment
3. With all of the sensors placed, the subject will step through a pitch to ensure the sensors will not interfere with the motions required.
4. If there is interference, adjust the sensors accordingly.

#### Use:

1. Allow the subject to warm up if they have not already completed the warm up exercises.
2. To collect pitching data with the Razor Sensors:
  - 2.1. Begin the stopwatch at the same moment as the data collection.
  - 2.2. “Lap” the stopwatch to document the time of the following points of interest:
    - 2.2.1. When the leading leg is lifted
  - 2.3. Record these times in the data sheet below.
  - 2.4. At the end of the session stop the data collection software and save using the following notation: Subject\_#\_MM\_DD\_YY\_Pitch\_#
3. Repeat step 2 for at least 10 pitches to produce the baseline for the subject on that day.
4. If collecting data on fatigue, refer to the Inducing Arm Fatigue protocol before recording data from more throws.

#### Breakdown:

1. Remove the tape and take off the sensors
2. Turn off the sensors
3. Sync SD cards with computer to collect data
4. Export data to computer as a .csv file.
5. Create a time file using the template

#### Data Analysis:

1. Edit the raw data .csv files
  - 1.1. Edit out the pre-pitch raw data in both the forearm and upper arm file using the time file

- 1.2. Edit out the post-pitch raw data in both the forearm and upper arm file by ensuring that there is the same number of rows in both data files
2. Use the MATLAB scripts in the following order to generate the fatigue detection
  - 2.1. datasorting.m
  - 2.2. EquationsRigidBody.m
  - 2.3. MaxForces.m
  - 2.4. SensitivityTesting.m

## Appendix E: Subject Survey: Post Session

### Subject Survey: Post Session

Purpose: To assess the level of fatigue and any pain experienced during experimentation.

Disclaimer: All feelings of fatigue, pain or discomfort will only be associated with your subject number and nothing shared with the investigators during any experimental session will be shared with external individuals (including, but not limited, to teammates, coaches, and athletic trainers)

#### Baseline Data Collection:

Before Baseline Data Collection (Before any pitches are thrown):

1. Are you using any upper body braces or orthopedic devices today?
2. How much weakness and/or fatigue (i.e., loss of strength) do you experience in your shoulder or elbow?



- a. Describe where you feel fatigue:
3. How much pain do you experience in your elbow?



- a. Describe where you feel pain:
- b. Describe what the pain feels like (sharp, dull):

After Baseline Data Collection (After the first 10 real pitches are thrown):

4. How much weakness and/or fatigue (i.e., loss of strength) do you experience in your shoulder or elbow?



- a. Describe where you feel fatigue:
5. How much pain do you experience in your elbow?



- a. Describe where you feel pain:
- b. Describe what the pain feels like (sharp, dull):
6. Are these pitches representative of your typical pitching?

Experimental Data Collection:

After Induced Arm Fatigue:

7. How much weakness and/or fatigue (i.e., loss of strength) do you experience in your shoulder or elbow?



- a. Describe where you feel fatigue:
8. How much pain do you experience in your elbow?



- a. Describe where you feel pain:
- b. Describe what the pain feels like (sharp, dull):

After Experimental Pitches (After at least 10 pitches are thrown post baseline collection):

9. How much weakness and/or fatigue (i.e., loss of strength) do you experience in your shoulder or elbow?



- a. Describe where you feel fatigue:
10. How much pain do you experience in your elbow?



- a. Describe where you feel pain:
- b. Describe what the pain feels like (sharp, dull):
11. Are these pitches representative of your typical pitching?

After the completion of this survey, confirm all information recorded with the subject, save survey as “Subject # Survey Post Session\_MM\_DD\_YY,” and enter information (excluding subject name) into master spreadsheet (Subject information)



## Appendix F: Induced Fatigue Protocol

### 1. Purpose

The purpose of this procedure is to induce arm fatigue targeting the primary muscles and joint actions of overhead throwing.

### 2. Scope

The scope of this procedure will apply to all voluntary subjects.

### 3. Responsibility

The research group and coaches of the voluntary subjects will be responsible for setting up experimental sessions.

### 4. Materials

The materials and equipment used in this testing are as follows:

- Arm Cycle

### 5. Procedure

Subjects will complete a series of arm cycle sprints as adapted from Pearcey et. al. after each set of pitches for as many sets can be safely conducted by the subject.

1. Subject begins cycling at speed of 50-70 RPM as the investigator increases resistance to a comfortable effort for the subject to maintain their speed.
  - This is the BASE resistance (Typically level 5-7 and will depend on subject fitness)
2. Subject maintains speed as investigator increases resistance of the arm cycle to an effort level where the subject is unable to talk while cycling
  - This is the SPRINT resistance (Typically upward of level 10 and will depend on subject fitness)
3. Subject completes 5 sprints in the following pattern
  1. 60 seconds of cycling at BASE resistance at approximately 50-70 RPM.
  2. 10 seconds sprinting at SPRINT resistance at approximately 50-70 RPM.
    - Allow 5 seconds of transition time between the base and the sprint to change the resistance, example:

Cycling	Base	Sprint	Base	Sprint	Base	Sprint	Base	Sprint	Base	Sprint
Start Time	0:00	1:05	1:20	2:25	2:40	3:45	4:00	5:05	5:20	6:25
End Time	1:00	1:15	2:20	2:35	3:40	3:55	5:00	5:15	6:20	7:25

## Appendix G: datasorting.m

```
function [sensordata_fa, sensordata_ua] = datasorting(x,y);

%time is in ms
%gyro is dps
%acc is in g's

clear; clc; close all;

x = input('Forearm data file \n', 's');
y = input('Upper arm data file \n', 's');

subject = input('Subject number\n', 's');
date = input('Date collected, separated by hyphens (Jan 31, 2018 is Jan-31-2018)\n', 's');
pitch = input('Pitch session\n', 's');
tic

x = input('Forearm data file \n', 's');
Forearm Data sort
data_fa=xlsread(x);
time=(data_fa(:,1)-data_fa(1,2))/1000; %creates time
% append time to the last column (#12)
sensordata_fa=[data_fa(:,2:7),time];
% sensordata_fa now has 7 columns: [Acc_x Acc_y Acc_z Gyro_X Gyro_Y Gyro_Z time]
Upper arm data sort
data_ua=xlsread(y);
time=(data_ua(:,1)-data_ua(1,2))/1000.0; %creates time
% append time to the last column (#7)
sensordata_ua=[data_ua(:,2:7),time];
% sensordata_ua now has 7 columns: [Acc_x Acc_y Acc_z Gyro_X Gyro_Y Gyro_Z time]
Filter
[b,a] = butter(2,0.05);
```

```
newdata_fa=filter(b,a,sensordata_fa);
newdata_ua=filter(b,a,sensordata_ua);
toc
Saving as data file
tic
%Saving the file with a dynamic name
newfile = strcat('Subject_', subject, '_date_', date, '_pitch_', pitch, '.mat');
save(newfile,'sensordata_fa', 'sensordata_ua', 'newdata_fa', 'newdata_ua');
toc
end
Published with MATLAB® R2018b
```

## Appendix H: EquationsRigidBody.m

Force and Moment Equations Using Alpha and Linear Acceleration

```
clc; clear all; close all
```

```
z = input('Sorted sensor data file \n', 's');
```

```
%subj_num = input('Subject Number \n') +2;
```

```
subj = input('Subject Number \n');
```

```
subject = num2str(subj);
```

```
session = input('Session Number for this Subject\n', 's');
```

```
load(z);
```

```
stat = xlsread('Subject_Intake_Survey Responses.xlsx');
```

```
g = [0 0 -9.81]; % m/s^2
```

```
z = input('Sorted sensor data file \n', 's');
```

Forearm Calculations

```
tic
```

```
mass_fa = stat(subj,10)* 0.016 * 4.45/9.81; % will be (data cell weight) * 0.016 from Winter's  
table
```

```
r_fa = [stat(subj,15) 0 0]/100; %COM to elbow distance
```

```
l_fa = stat(subj,11)/100; %total length of forearm in meters
```

```
lin_acc_fa = [newdata_fa(:,1), newdata_fa(:,2), newdata_fa(:,3)]*9.81; % linear acceleration
```

```
[m_fa n_fa] = size(newdata_fa);
```

```
alpha_fa = zeros(m_fa,3);
```

```
for i = 2: m_fa
```

```
    alpha = [(newdata_fa(i,4)-newdata_fa(i-1,4)), (newdata_fa(i,5)-newdata_fa(i-1,5)),  
(newdata_fa(i,6)-newdata_fa(i-1,6))]/(newdata_fa(2,7)-newdata_fa(3,7)); % angular acceleration
```

```
    alpha_fa(i-1,1:3) = alpha;
```

```
end
```

```
alpha_fa(m_fa, 1:3) = alpha_fa(m_fa-1, 1:3);
```

```
I_fa = (1/12) * mass_fa * (l_fa)^2; % moment of inertia of forearm
```

```

%Sum of Forces FA
f_elbow = -(mass_fa * lin_acc_fa) + (mass_fa * g);
f_elbow_mag = sqrt((f_elbow(:,1)).^2 + (f_elbow(:,2)).^2 + (f_elbow(:,3)).^2);

h=figure;
ax1 = subplot(4,2,1);
plot((sensordata_fa(:,7)-sensordata_fa(1,7)),f_elbow_mag(:));
hold on

title('Elbow Force (N)');
xlabel('time (s)');
ylabel('force (N)');

%save variable
save(z,'f_elbow_mag','-append');

%Sum of Moments FA
B = repmat(r_fa,[size(f_elbow(:,1)) 1]);
C = cross(B(1:size(B),:),f_elbow(1:size(B),:));
A = (I_fa * alpha_fa);
t_elbow = A + C;

t_elbow_mag = sqrt((t_elbow(:,1)).^2 + (t_elbow(:,2)).^2 + (t_elbow(:,3)).^2);
figure
ax2 = subplot(3,2,2);
plot((sensordata_fa(:,7)-sensordata_fa(1,7)),t_elbow_mag(:,1));
hold on

title('Elbow Torque (N)');
xlabel('time (s)');
ylabel('moment (Nm)');
save(z,'t_elbow_mag','-append');

```

### Upperarm Calculations

```
mass_ua = stat(subj,10)* 0.028 * 4.45/9.81; % will be (data cell weight) * 0.028 from Winter's table
```

```
r_uad = [stat(subj,16) 0 0]/100;
```

```
r_uap = [-(stat(subj,12)-stat(subj,16)) 0 0]/100;
```

```
R_ua = stat(subj,14)/(2*pi)/100; % radius of upper arm meters (will be a data cell value)
```

```
lin_acc_ua = [newdata_ua(:,1), newdata_ua(:,2), newdata_ua(:,3)]*9.81; % linear acceleration
```

```
[m_ua n_ua] = size(newdata_ua);
```

```
alpha_ua = zeros(m_ua,3);
```

```
for i = 2: m_ua
```

```
    alpha = [(newdata_ua(i,4)-newdata_ua(i-1,4)), (newdata_ua(i,5)-newdata_ua(i-1,5)),  
(newdata_ua(i,6)-newdata_ua(i-1,6))]/(newdata_ua(2,7)-newdata_ua(3,7)); % angular acceleration
```

```
    alpha_ua(i-1,1:3) = alpha;
```

```
end
```

```
alpha_ua(m_ua, 1:3) = alpha_ua(m_ua-1, 1:3);
```

```
I_ua = (1/2) * mass_ua * R_ua^2; % moment of inertia of upper arm
```

```
%Sum of Forces UA
```

```
f_shoulder = (mass_ua * lin_acc_ua) - f_elbow - (mass_ua * g);
```

```
f_shoulder_mag = sqrt((f_shoulder(:,1)).^2 + (f_shoulder(:,2)).^2 +(f_shoulder(:,3)).^2);
```

```
save(z,'f_shoulder_mag','-append');
```

```
ax3 = subplot(4,1,3);
```

```
plot((sensordata_ua(:,7)-sensordata_ua(1,7)),f_shoulder_mag);
```

```
title('Shoulder Force (N)');
```

```
xlabel('time (s)');
```

```
ylabel('force (N)');
```

```

%Sum of Moments UA
D = repmat(r_uap,[size(f_shoulder(:,1)) 1]);
E = cross(D(1:size(D),:),f_shoulder(1:size(D),:));
F = repmat(r_uad,[size(f_elbow(:,1)) 1]);
G = cross(F(1:size(F),:),f_shoulder(1:size(F),:));
H = (I_ua * alpha_ua);
t_shoulder = H - t_elbow - E - G;

t_shoulder_mag = sqrt((t_shoulder(:,1)).^2 + (t_shoulder(:,2)).^2 +(t_shoulder(:,3)).^2);

save(z,'t_shoulder_mag','-append');

ax4 = subplot(4,1,4);
plot((sensordata_ua(:,7)-sensordata_ua(1,7)),t_shoulder_mag);
title('Shoulder Moment (N*m)');
xlabel('time (s)');
ylabel('force (N)');

linkaxes([ax1,ax2,ax3,ax4],'x')

fname = 'Y:\Graphs\Pitching\';

%subject = input('Subject number\n', 's');
%session = input('Session Number for this Subject\n', 's');

%Saving the file with a dynamic name
filename = strcat('Subject_', subject, '_session_', session, '_EqnRigid');
fullfile = strcat(fname, filename);
saveas(gcf, fullfile, 'bmp');
toc

```





## Appendix I: MaxForces.m

Find Max Forces Based on Time Data

```
clc; clear all; close all;

z = input('Sorted sensor data file \n', 's');
t = input('Time File \n', 's');
subject = input('Subject number\n', 's');
session = input('Session Number for this Subject\n', 's');

tic

load(z);

pitch_times = xlsread(t);
[m n] = size(pitch_times(:,1:2));
felb_t = [f_elbow_mag, sensordata_fa(:,7)];
create_range = [];
for i = 2:size(pitch_times(:,2))
    %create_range = [create_range; pitch_times(i-1,2),pitch_times(i,2)];
    time_range = find(felb_t(:,2)>pitch_times(i-1,2) & felb_t(:,2)<pitch_times(i,2));
    create_range = [create_range; min(time_range),max(time_range)];
end

max_forces_elb = [];
for h = 1:size(create_range(:,1))
    max_f = max(felb_t(create_range(h,1):create_range(h,2),1));
    max_forces_elb = [max_forces_elb; max_f];
end

h = figure;
subplot(4,1,1)

scatter([1:(size(pitch_times(:,1:2))-1)],max_forces_elb);
hold on
```

```

title('Maximum Elbow Force During Each Pitch');
xlabel ('Pitch Count');
ylabel('Max Forces (N)');

save(z,'max_forces_elb','-append');

z = input('Sorted sensor data file \n', 's');
telb_t = [t_elbow_mag, sensordata_fa(:,7)];
create_range = [];
for j = 2:size(pitch_times(:,2))
    %create_range = [create_range; pitch_times(i-1,2),pitch_times(i,2)];
    time_range = find(telb_t(:,2)>pitch_times(j-1,2) & telb_t(:,2)<pitch_times(j,2));
    create_range = [create_range; min(time_range),max(time_range)];
end

max_tor_elb = [];
for h = 1:size(create_range(:,1))
    max_t = max(telb_t(create_range(h,1):create_range(h,2),1));
    max_tor_elb = [max_tor_elb; max_t];
end

figure
subplot(4,2,1)
scatter([1:(size(pitch_times(:,1:2))-1)],max_tor_elb);
hold on
title('Maximum Elbow Torque During Each Pitch');
xlabel ('Pitch Count');
ylabel('Max Torque (Nm)');

save(z,'max_tor_elb','-append');
fsho_t = [f_shoulder_mag, sensordata_fa(:,7)];
create_range = [];

```

```

for i = 2:size(pitch_times(:,2))
    %create_range = [create_range; pitch_times(i-1,2),pitch_times(i,2)];
    time_range = find(fsho_t(:,2)>pitch_times(i-1,2) & fsho_t(:,2)<pitch_times(i,2));
    create_range = [create_range; min(time_range),max(time_range)];
end

max_forces_sho = [];
for h = 1:size(create_range(:,1))
    max_f = max(fsho_t(create_range(h,1):create_range(h,2),1));
    max_forces_sho = [max_forces_sho; max_f];
end
figure
subplot(4,1,3)
scatter([1:(size(pitch_times(:,1:2))-1)],max_forces_sho);
hold on
title('Maximum Shoulder Force During Each Pitch');
xlabel ('Pitch Count');
ylabel('Max Forces (N)');

tsho_t = [t_shoulder_mag, sensordata_fa(:,7)];
create_range = [];
for i = 2:size(pitch_times(:,2))
    %create_range = [create_range; pitch_times(i-1,2),pitch_times(i,2)];
    time_range = find(tsho_t(:,2)>pitch_times(i-1,2) & tsho_t(:,2)<pitch_times(i,2));
    create_range = [create_range; min(time_range),max(time_range)];
end

max_tor_sho = [];
for h = 1:size(create_range(:,1))
    max_f = max(tsho_t(create_range(h,1):create_range(h,2),1));
    max_tor_sho = [max_tor_sho; max_f];
end

```

```

end

subplot(4,1,4)
scatter([1:(size(pitch_times(:,1:2))-1)],max_tor_sho);
hold on
title('Maximum Shoulder Torque During Each Pitch');
xlabel ('Pitch Count');
ylabel('Max Forces (N)');

save(z,'max_forces_elb','-append');
save(z,'max_tor_elb','-append');
save(z,'max_forces_sho','-append');
save(z,'max_tor_sho','-append');

allmax = [max_forces_elb, max_tor_elb, max_forces_sho, max_tor_sho];

%Saving the file with a dynamic name
xlpath = 'Y:\MaxForces\';
xlname = strcat('Subject_', subject, '_session_', session, '_MaxForces');
fullxlname = strcat(xlpath, xlname, '.xls');

xlswrite(fullxlname,allmax);

fname = 'Y:\Graphs\Pitching\';
filename = strcat('Subject_', subject, '_session_', session, '_MaxForces');
fullfile = strcat(fname, filename);
saveas(gcf, fullfile, 'bmp');
toc
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```

## Appendix J: StatAnalysis.m

Statistical Analysis

```
clc; clear all
```

```
%close all
```

```
z = input('Sorted sensor data file \n', 's');
```

```
subject = input('Subject Number\n', 's');
```

```
session = input('Session Number for this Subject\n', 's');
```

```
tic
```

```
load(z);
```

```
[m n] = size(max_forces_elb);
```

```
toc
```

```
z = input('Sorted sensor data file \n', 's');
```

Moving Average

```
tic
```

```
s = mean(max_tor_elb(1:2));
```

```
moving_mean = [s];
```

```
for i = 3:m
```

```
    mov = mean(max_tor_elb(1:i));
```

```
    moving_mean = [moving_mean; mov];
```

```
end
```

```
toc
```

```
%f1 = figure;
```

```
%title('Subject 1, Session 2');
```

```
subplot(4,2,1);
```

```
plot(moving_mean);
```

```
title({'Cumulative Average'; 'of the Elbow Torques'});
```

```
xlabel('Pitch Count');
```

```
ylabel('Moment (Nm)');
```

Moving Standard Deviation

tic

```
s1 = std(max_tor_elb(1:2));
```

```
moving_stdev = [s1];
```

```
for i = 3:m
```

```
    mov = std(max_tor_elb(1:i));
```

```
    moving_stdev = [moving_stdev; mov];
```

```
end
```

toc

```
subplot(4,2,3);
```

```
plot(moving_stdev);
```

```
title({'Cumulative Standard Deviation';'of the Elbow Torques'});
```

```
xlabel ('Pitch Count');
```

```
ylabel ('Moment (Nm)');
```

```
save(z,'moving_mean','-append');
```

```
save(z,'moving_stdev','-append');
```

Save graph

```
% fname = 'Y:\Graphs\Pitching\';
```

```
%
```

```
% filename = strcat('Subject_', subject, '_session_', session, '_MovingMean');
```

```
% fullfile = strcat(fname, filename);
```

```
% %saveas(gcf, fullfile, 'bmp');
```

```
% %fprintf('Done Saving\n');
```

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## Appendix K: SensitivityTesting.m

```
% this file is a script created to open data in .csv format, plot the data
% in various ways, and then apply the moving average function to do a
% sliding window analysis of the data. It calls the movingAve.m script for
% the sliding window analysis.

clear; clc; close all;

specify file
%fileName='Specimen_RawData_1.csv';

z = input('Sorted sensor data file \n', 's');
% W=input('Window Size? \n');
W = 6;
start = 10;
accdev = input('Enter acceptable deviation level \n');
dev = num2str(accdev*100);
base = num2str(W);
subject = input('Subject number\n', 's');
session = input('Session Number for this Subject\n', 's');
load(z);

z = input('Sorted sensor data file \n', 's');
Create the first window and baselines
dbclear if naninf

%this sets the window to 20 data points
N=ceil(W/2);
%N = W - 1;
[m, n] = size(max_forces_elb);
%setbase = input('How many base pitches are there? \n');
Elbow Torques
%moving mean and stdev
```

```

m_meanet = movmean(max_tor_elb,N);
m_stdevet = movstd(max_tor_elb,N);

base_meanet = mean(max_tor_elb(1:start,:));
base_stdevet = std(max_tor_elb(1:start,:));
rangeet = base_stdevet * accdev;
subplot(4,2,1)
%plot([1;W],[base_meanet + base_stdevet;base_meanet + base_stdevet],'r');
hold on
%plot([1;W],[base_meanet - base_stdevet;base_meanet - base_stdevet],'b');
title('Detection of Increased Deviation in Elbow Torque');
xlabel('Pitch Count');
ylabel('Moment (N*m)');
scatter([1:size(max_tor_elb)],max_tor_elb, 'm');
% plot([1:size(max_tor_elb)],m_meanet,'b')
% plot([1:size(max_tor_elb)],m_stdevet,'r')
hold on

% Check the next windows
bottomet = start - N;
for i = 1:floor((m-start+N)/N)-1
    topet = bottomet + W;
    ouchxet = mean(bottomet,topet);
    test_meanet = mean(max_tor_elb(bottomet:topet));
    test_stdevet = std(max_tor_elb(bottomet:topet));

    %i
    if test_stdevet > (base_stdevet + rangeet)
        ouch = ((test_stdevet/base_stdevet)-1) * 100;
        plot([bottomet;topet],[test_meanet + test_stdevet;test_meanet + test_stdevet],'r');

```



```

plot([bottomet;topet],[(test_meanet - test_stdevet);(test_meanet - test_stdevet)],'b');
plot([bottomet;topet],[(test_meanet + test_stdevet);(test_meanet + test_stdevet)],'*r');
plot([bottomet;topet],[(test_meanet - test_stdevet);(test_meanet - test_stdevet)],'*b');
plot([bottomet;bottomet],[(test_meanet - test_stdevet);(test_meanet + test_stdevet)]);
plot([topet;topet],[(test_meanet - test_stdevet);(test_meanet + test_stdevet)]);
fprintf("Torques at the elbow have become excessively variable during pitches %d - %d. \n
The standard deviation has increased by %.2f%% compared to the healthy baseline. \n Check if
pitcher has fatigued \n\n", bottomet, topet, ouch);
end
bottomet = (start-N)+(i*N);
end
Saving the file with a dynamic name
fname = 'Y:\SensitivityStudy\';

filename = strcat('Subject_', subject, '_session_', session, '_base_', base, '_dev_', dev,
'_SlideWindow');
fullfile = strcat(fname, filename);
saveas(gcf, fullfile, 'bmp');
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```